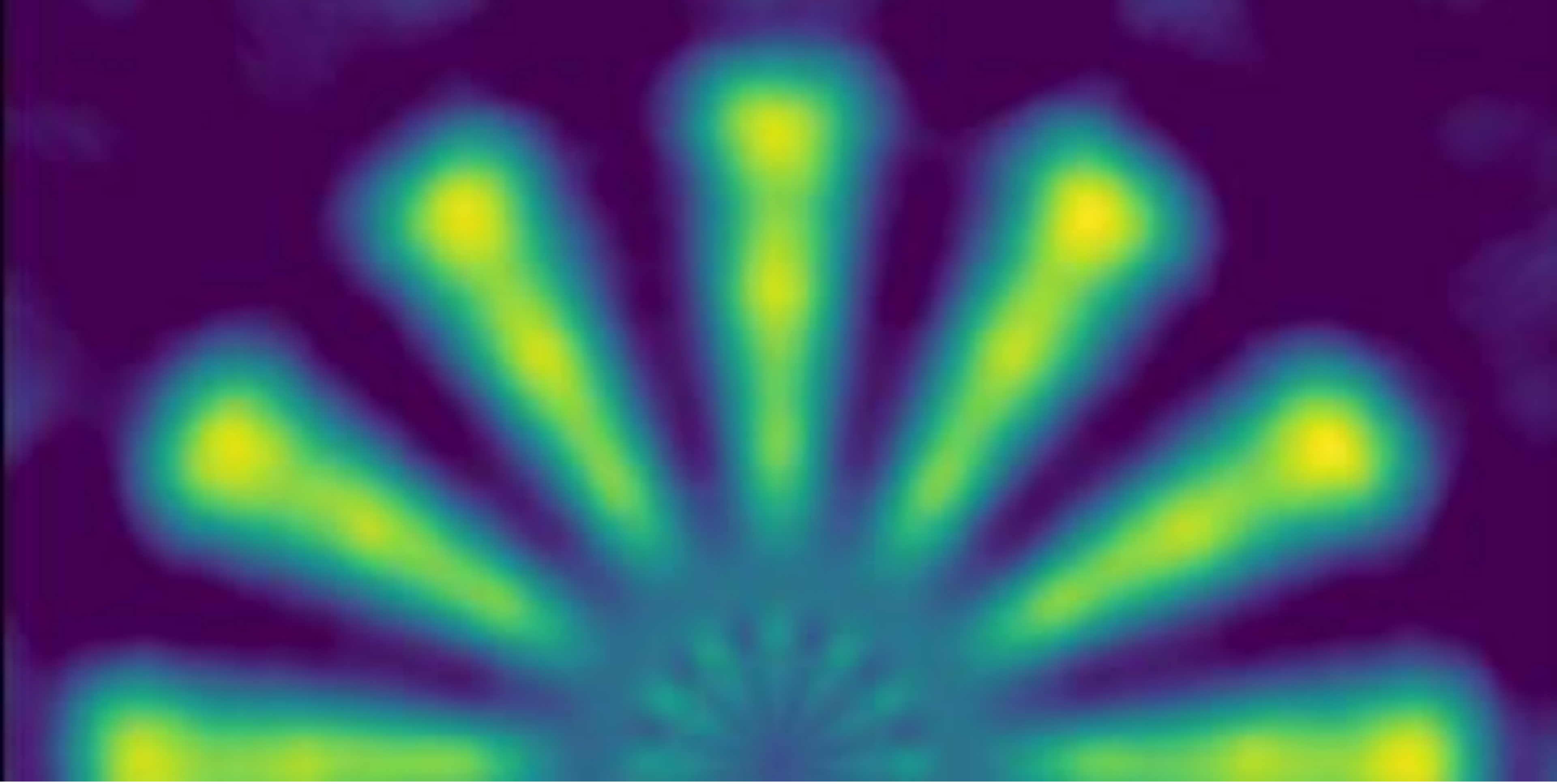


Tomography with Fast Neutrons

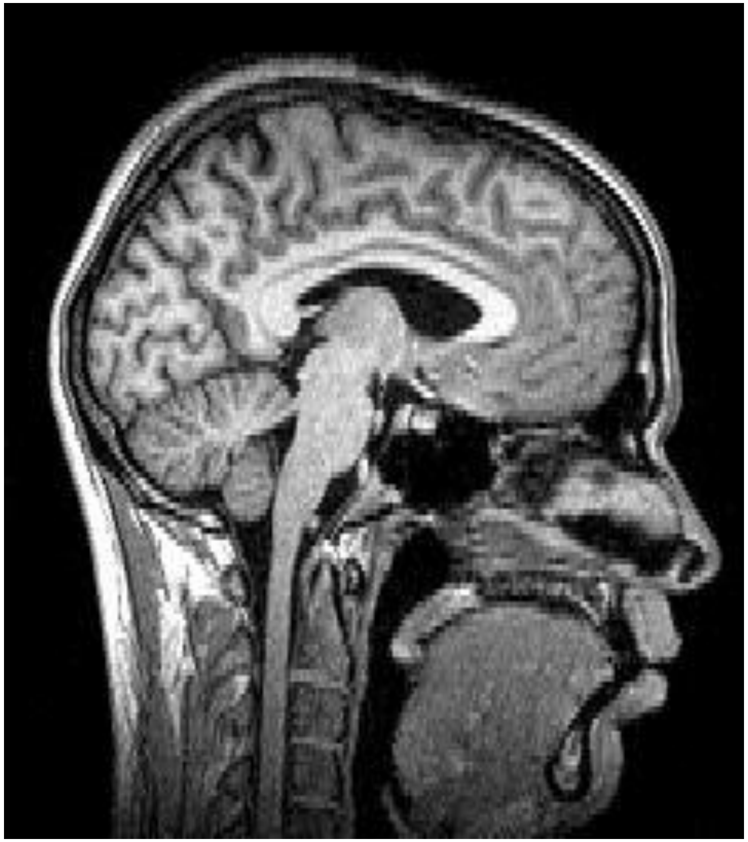
Aenne Abel, Master‘s Project
Silicon Detector R&D Meeting | 18.06.2024
III. Physikalisches Institut B, RWTH Aachen University

Tomography – Non-destructive View Inside Object

Radiographic image

Dr Matt A. Morgan

Tomographic image



Wikipedia

Reconstruction Process

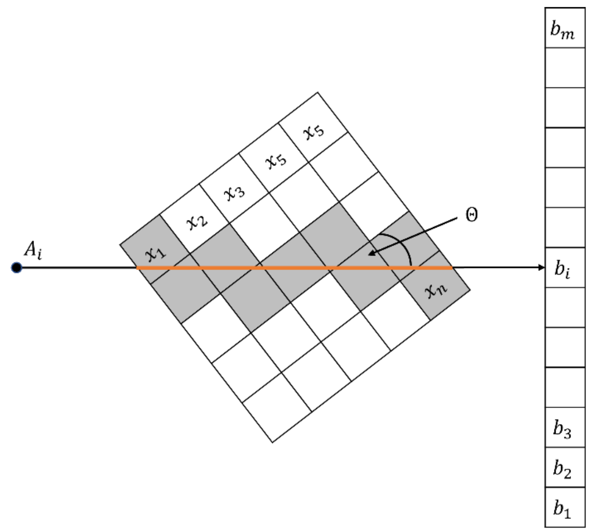
- Measure reference counts without object I_0
- Measure counts with object I
- Assume exponential law

$$\vec{b} = -\ln\left(\frac{I}{I_0}\right) = \int \mu(x,y)ds$$

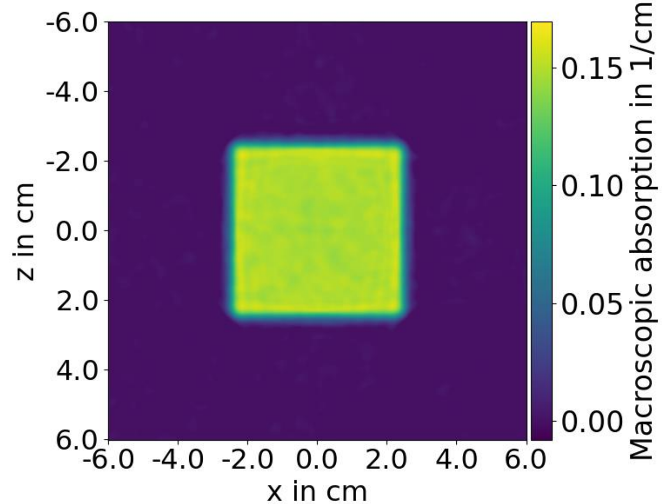
- Interpret problem as matrix equation:

$$\vec{b} = A\vec{x}$$

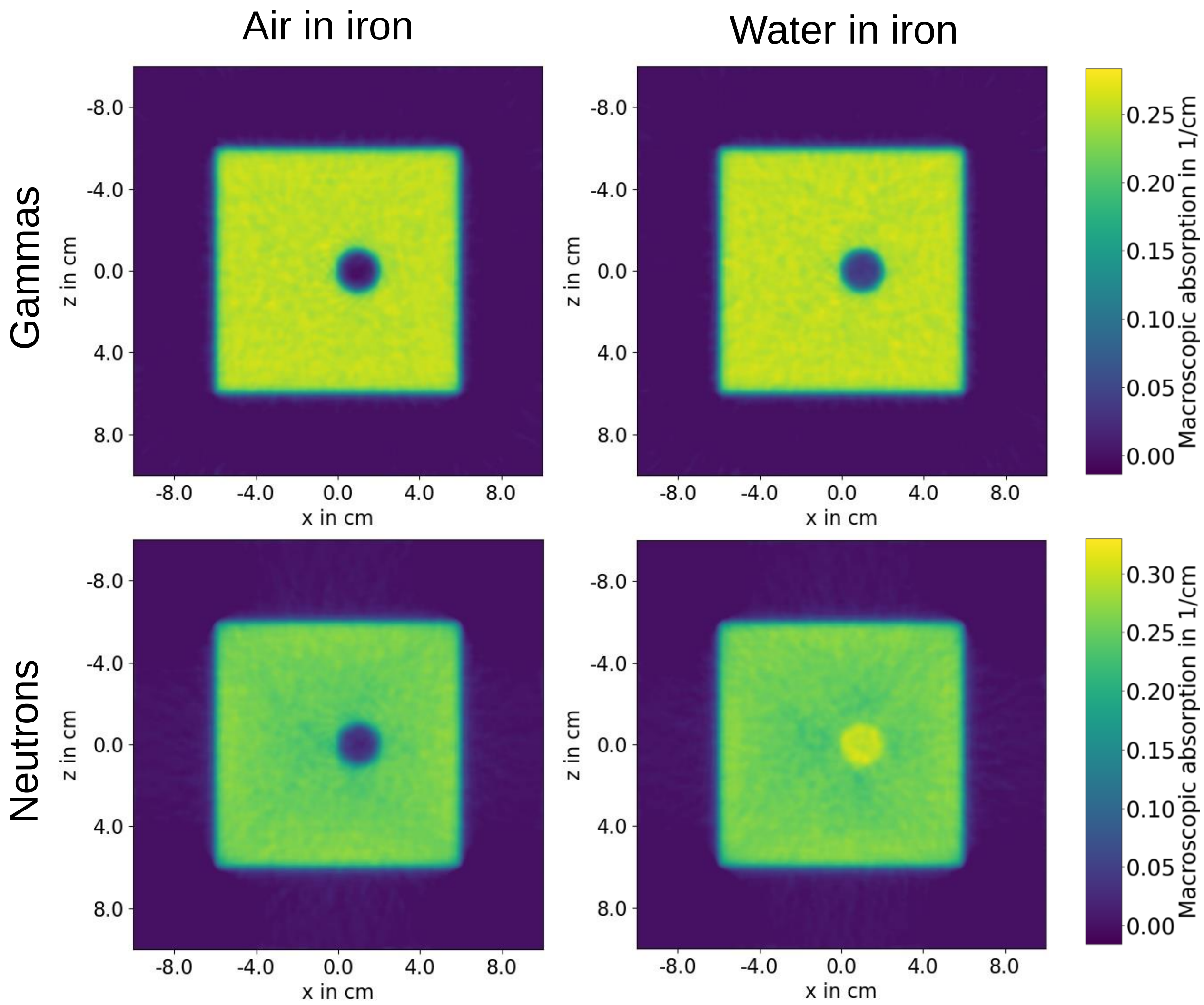
- A: Weight of beam going through element $\vec{x}$
- Minimization problem for $\vec{x}$
- Simultaneous Iterative Reconstruction Technique (SIRT) with ASTRA Toolbox



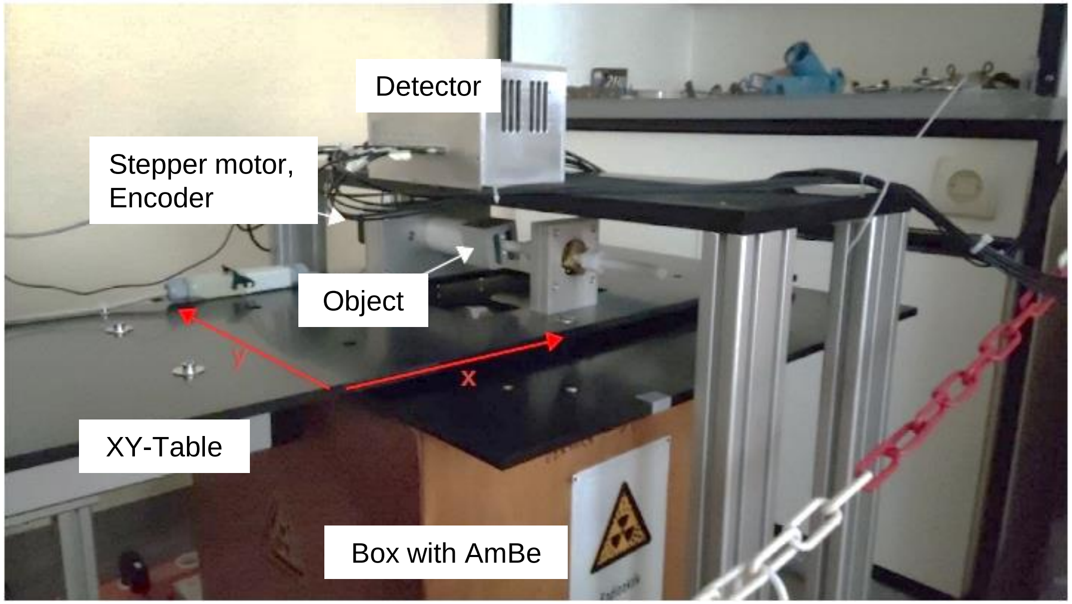
Adapted from G. A. Jones, P.Huthwaite



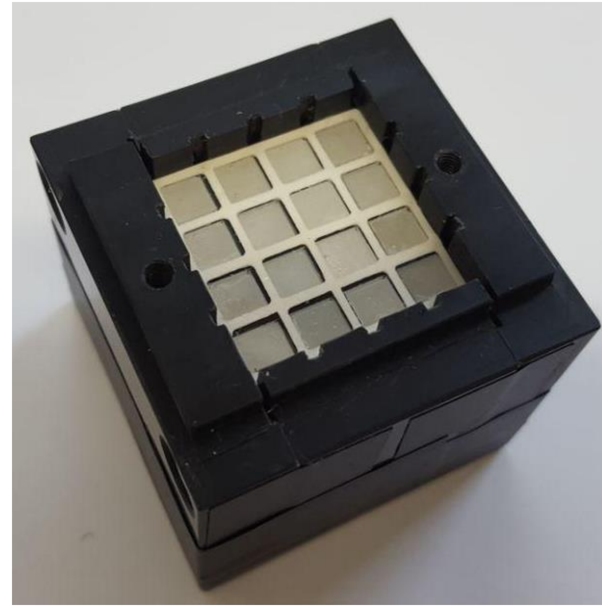
Why use Neutrons?



Measurement Setup



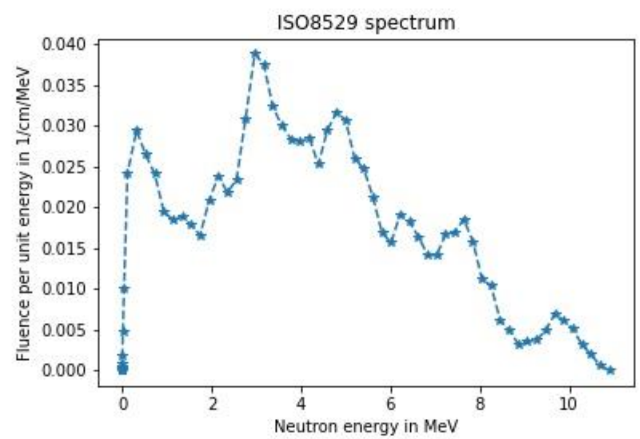
Nina Höflich



Christoph Günther

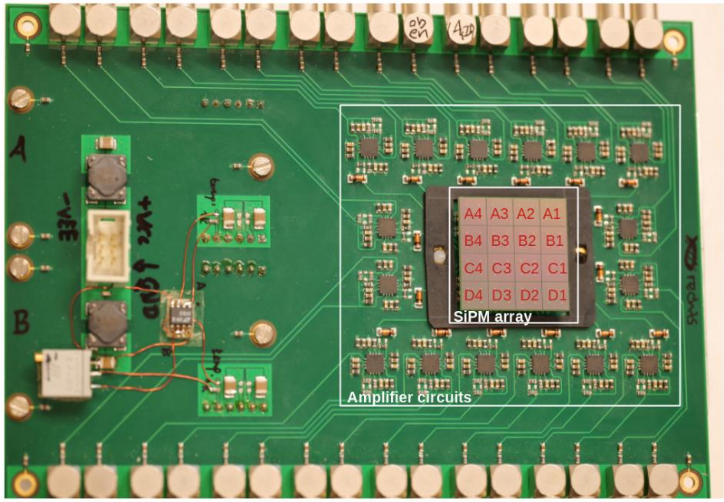
$$^{241}\mathrm{Am} \rightarrow ^{237}\mathrm{Np}^* + \alpha \rightarrow ^{237}\mathrm{Np} + \gamma\,(59.5\,\mathrm{keV}) + \alpha$$

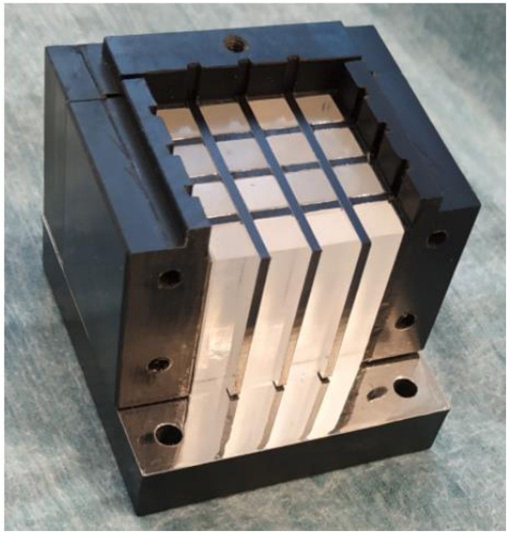
$$\alpha + ^{9}\mathrm{Be} \rightarrow ^{12}\mathrm{C}^* + \mathrm{n} \rightarrow ^{12}\mathrm{C} + \gamma\,(4.44\,\mathrm{MeV}) + \mathrm{n}$$

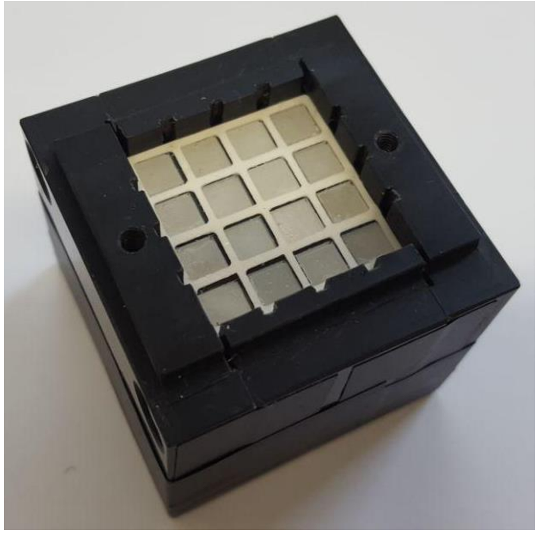


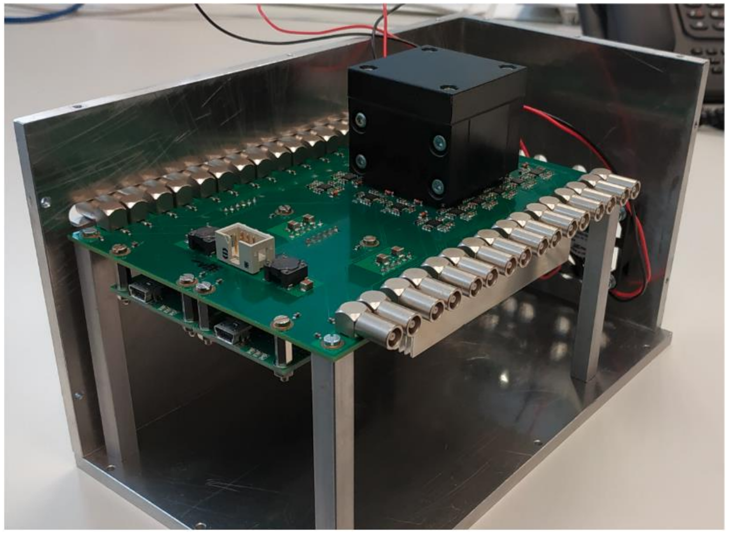
Detector

- (Trans-)Stilbene crystals (5 × 5 × 25) mm³
- Reflective foil ESR
- Coupling pad from PLA filled with elastosil
- SiPM Hamamatsu MPPC array
- PCB for power supply and amplification





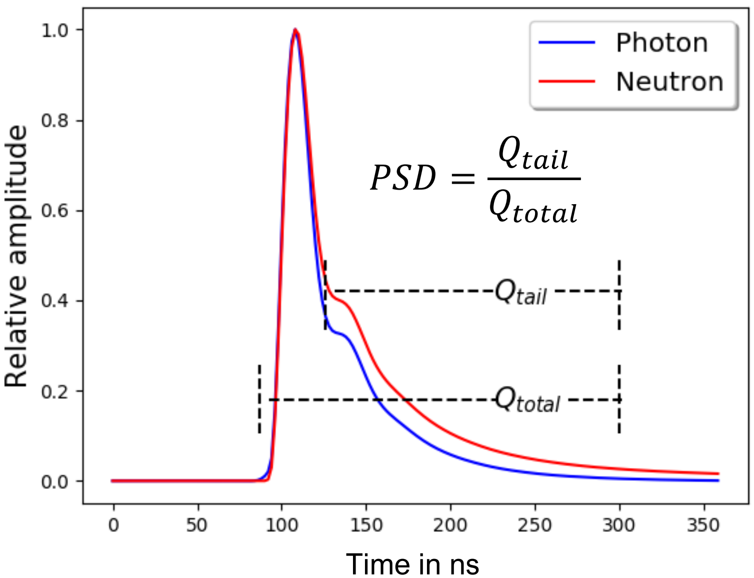




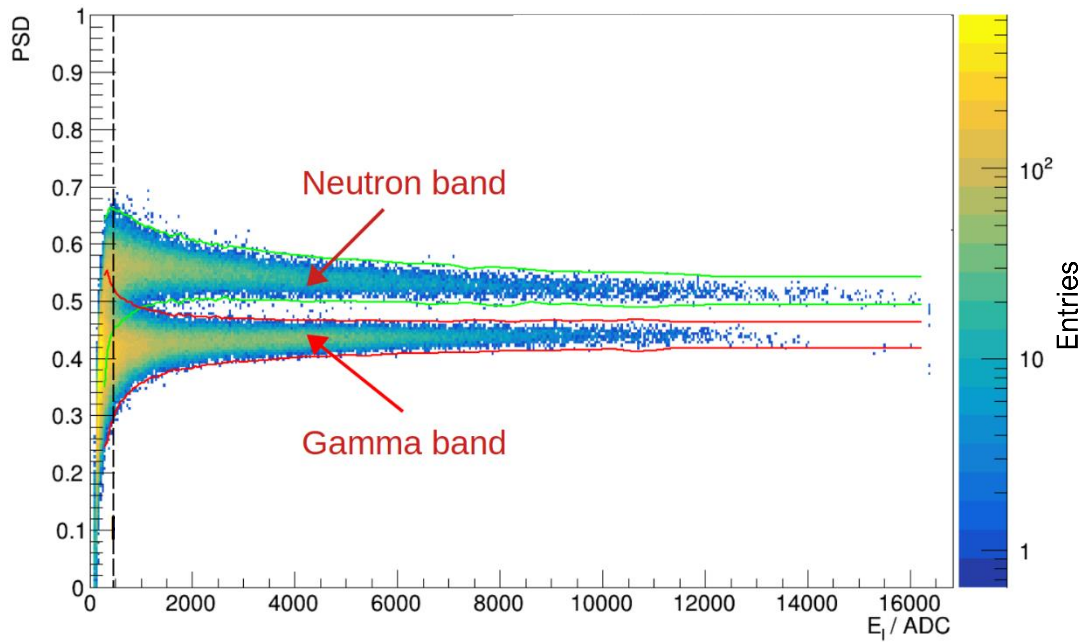
Pulse Shape Discrimination (PSD)

Particle	τ_{fast} in ns	$\tau_{\text{intermediate}}$ in ns	τ_{slow} in ns
Neutron	5,01 (95 %)	27,70 (4 %)	253,19 (1 %)
Gamma	5,21 (95 %)	21,33 (3 %)	137,77 (2 %)

- Measure integral over whole pulse Q_{total}
- Measure integral over tail part of the pulse Q_{tail}
- PSD variable $\frac{Q_{tail}}{Q_{total}}$ in general higher for neutrons



Christian Teichrib

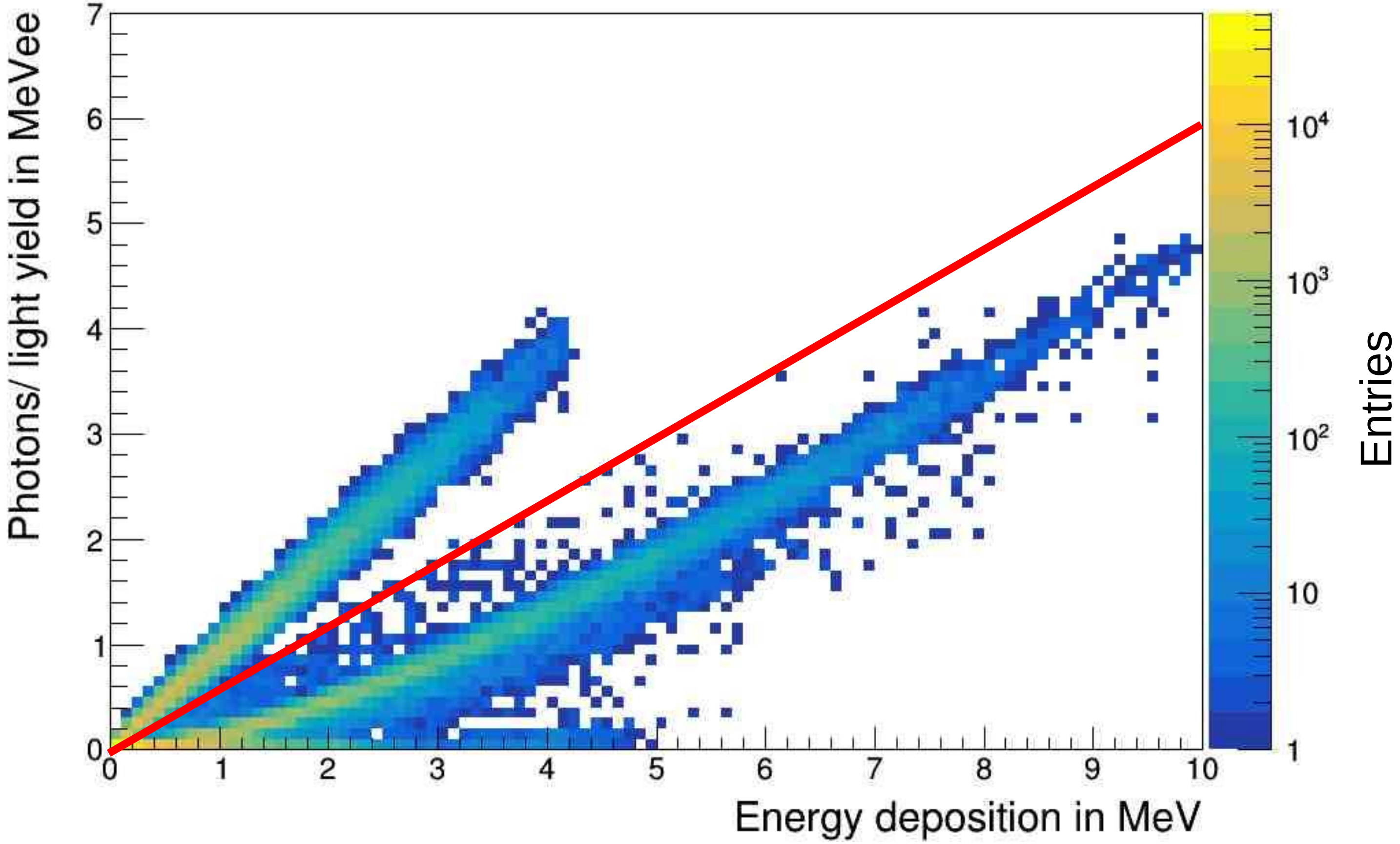


Nina Höflich

Simulation Realistic Detector

- Up until now, PSD not possible in simulation
- Separation over quenching effect

$$\frac{\mathrm{d}L}{\mathrm{d}x} = \frac{S\frac{\mathrm{d}E}{\mathrm{d}x}}{1 + kB\frac{\mathrm{d}E}{\mathrm{d}x}}$$



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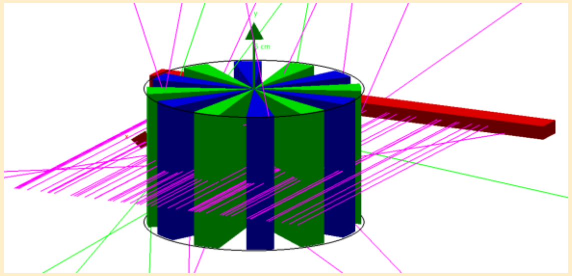
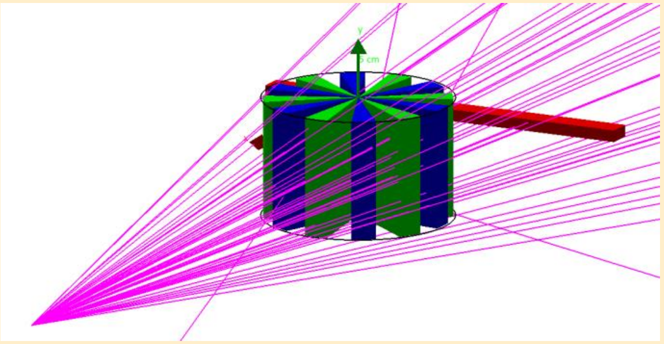
Detector Simulations

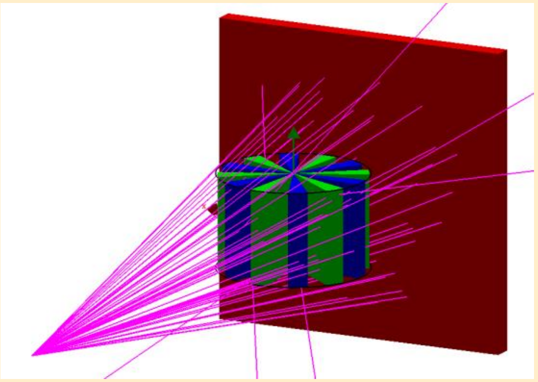
Parallel beam



Cone beam

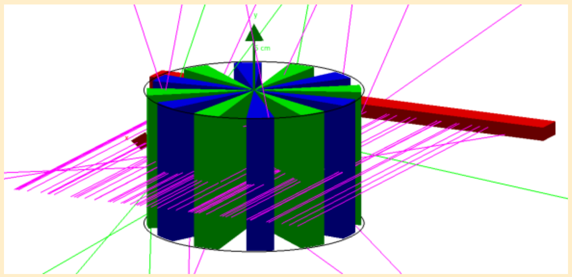


Cone beam 3D

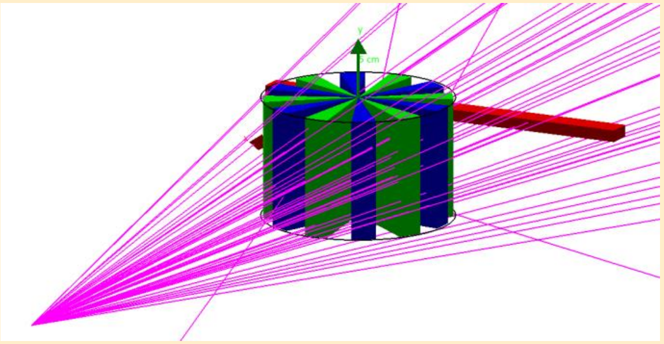


Detector Simulations

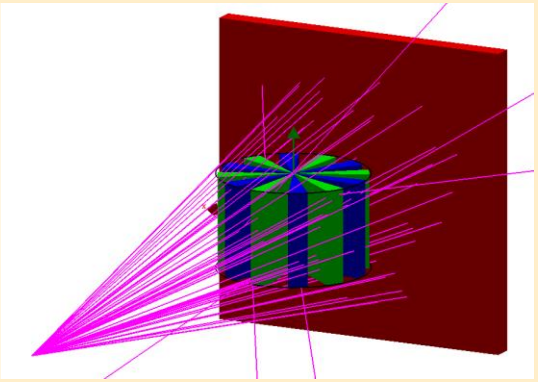
Parallel beam



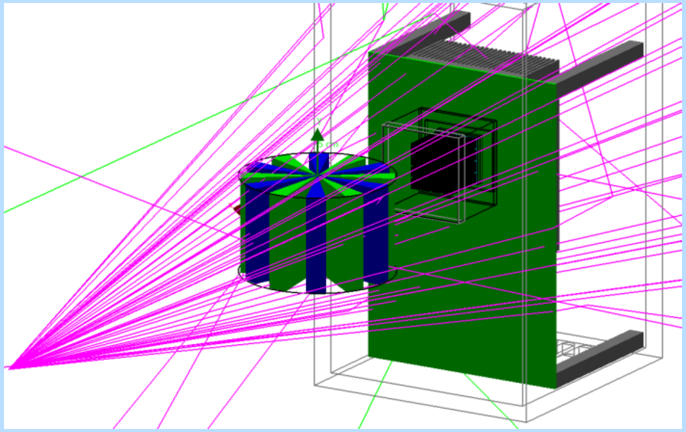
Cone beam



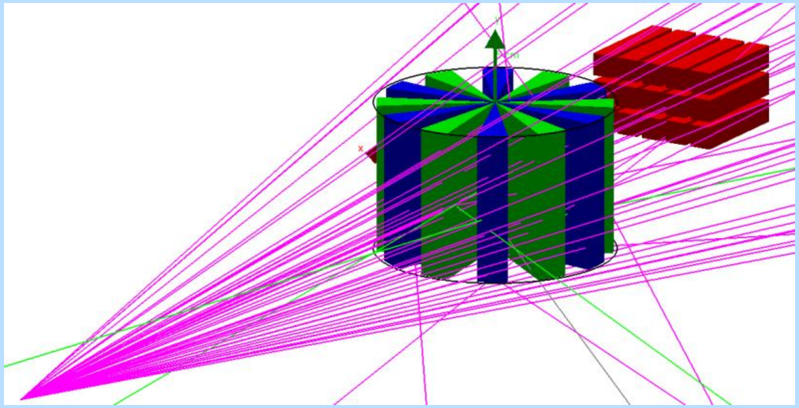
Cone beam 3D



Realistic detector

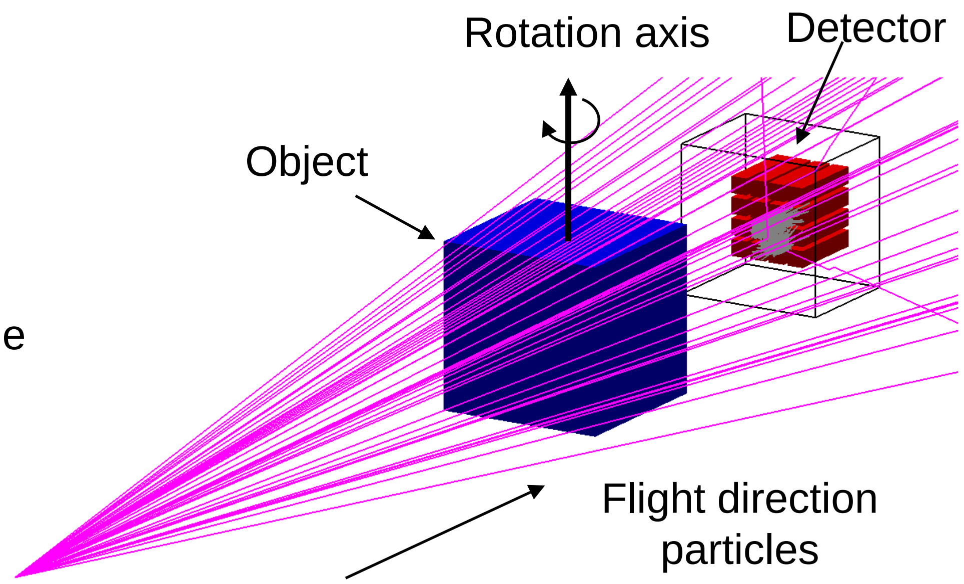


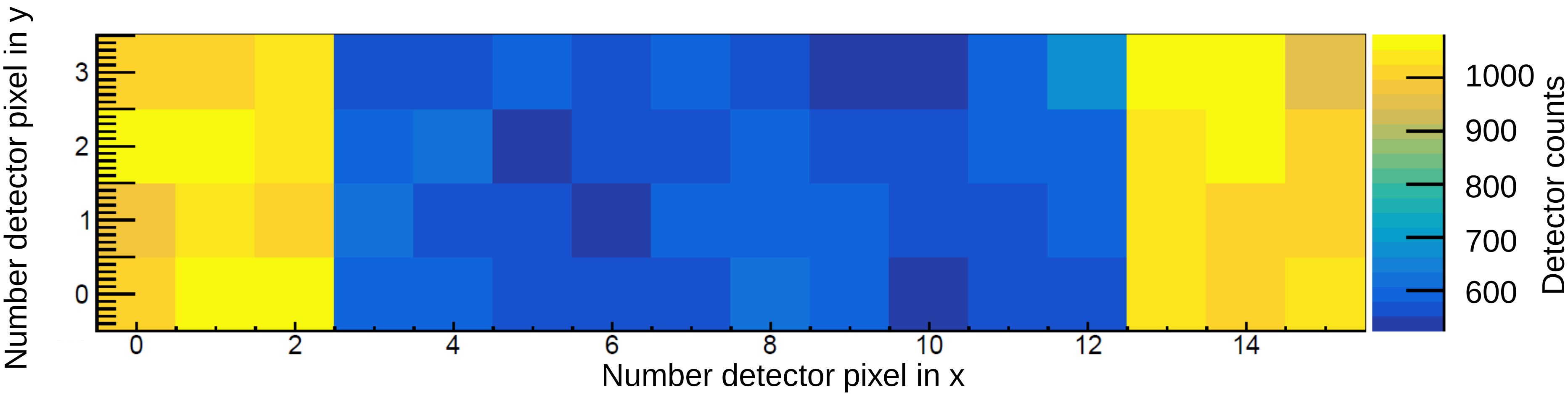
Manipulated detector



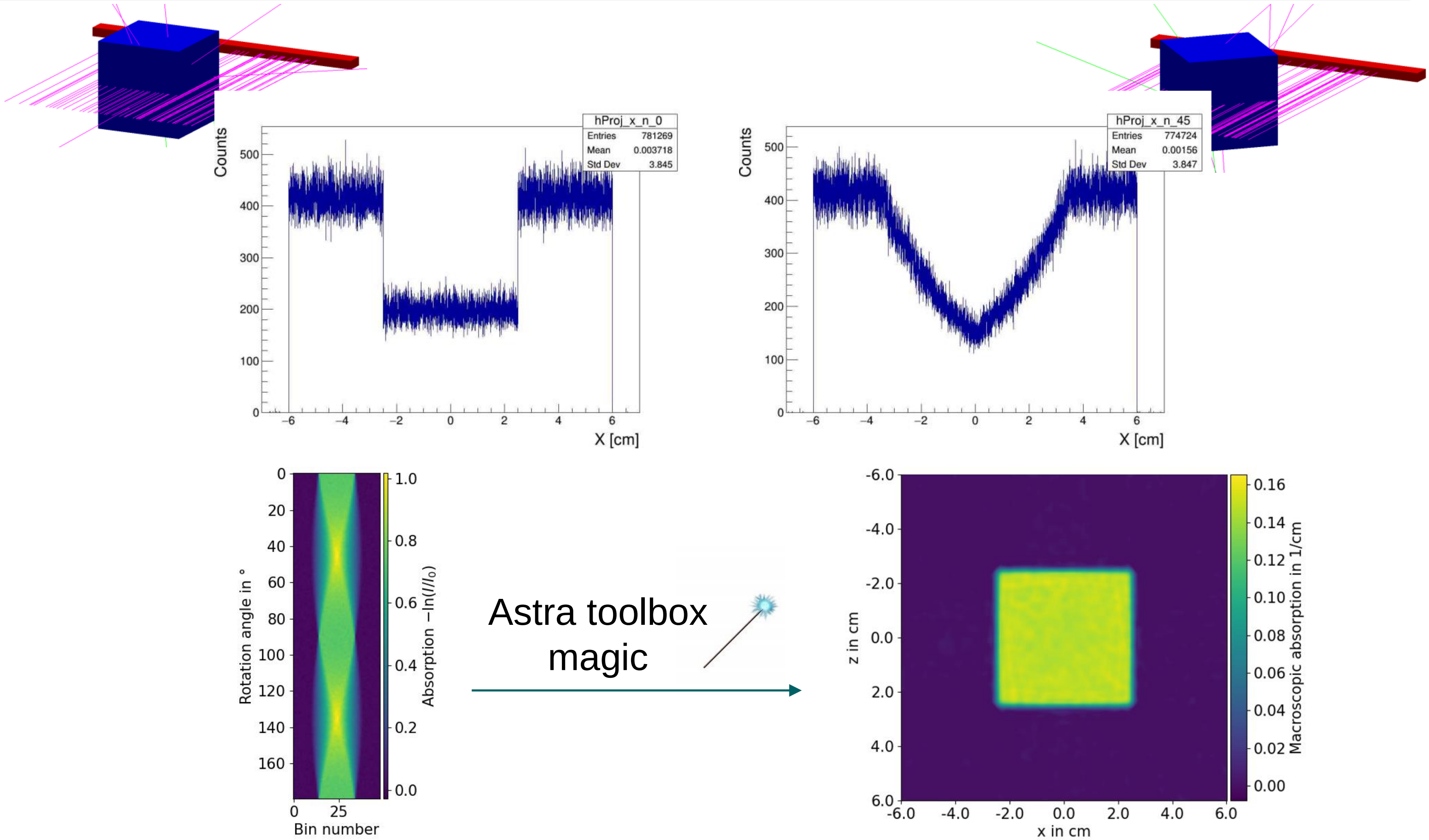
Generating Particle Counts with GEANT4

- Simulation of particles, objects and detectors with GEANT4
- Detector response:
  - Idealized: Store exact position of particle
  - Realistic: Store deposited energy and scintillation light





Reconstruction Steps



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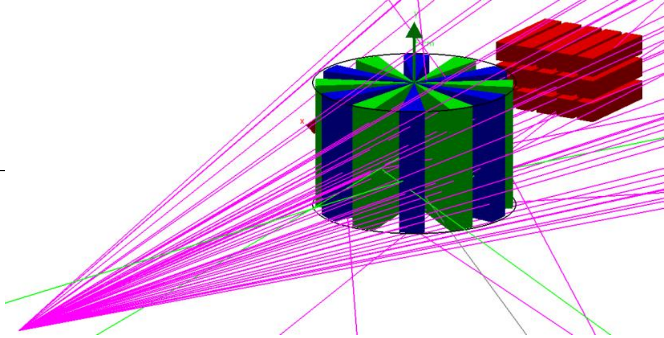
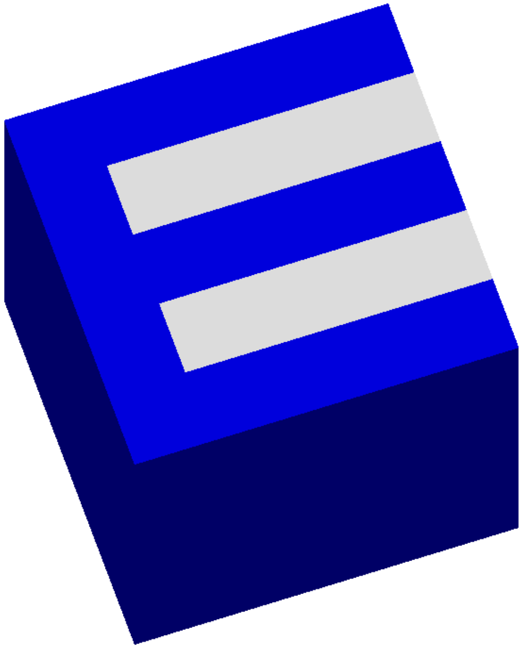
Quality Criteria Objects

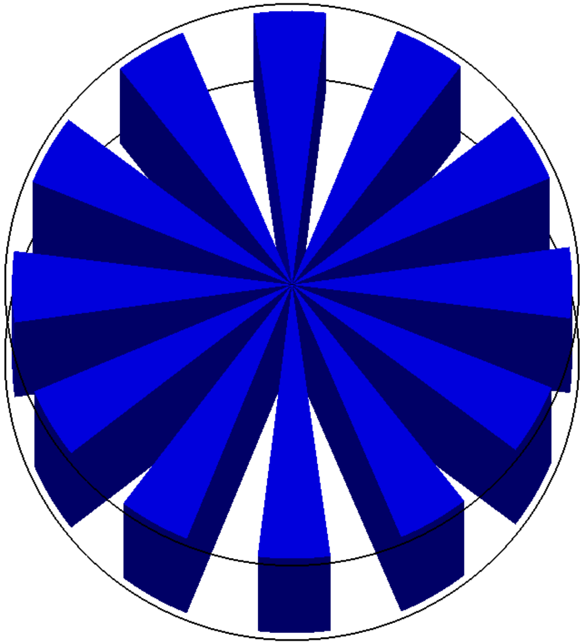


- Simulate objects with realistic detector
- Four or five object positions

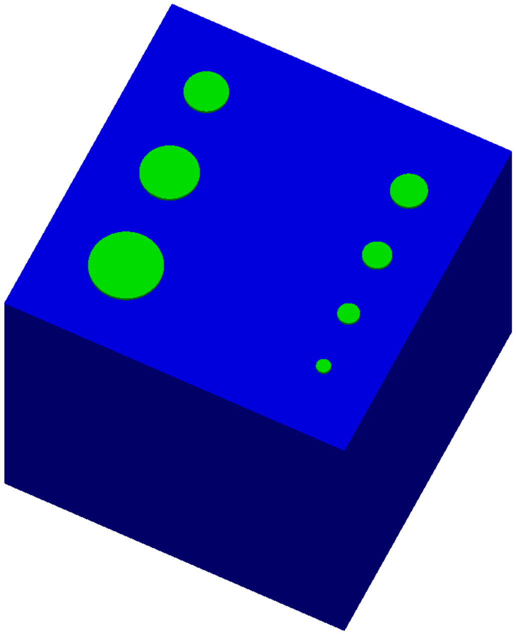
E:
Edge quality

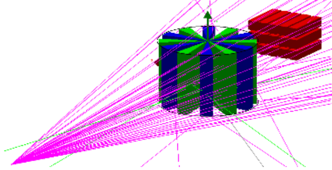


Siemens star:
Spatial resolution
Edge quality



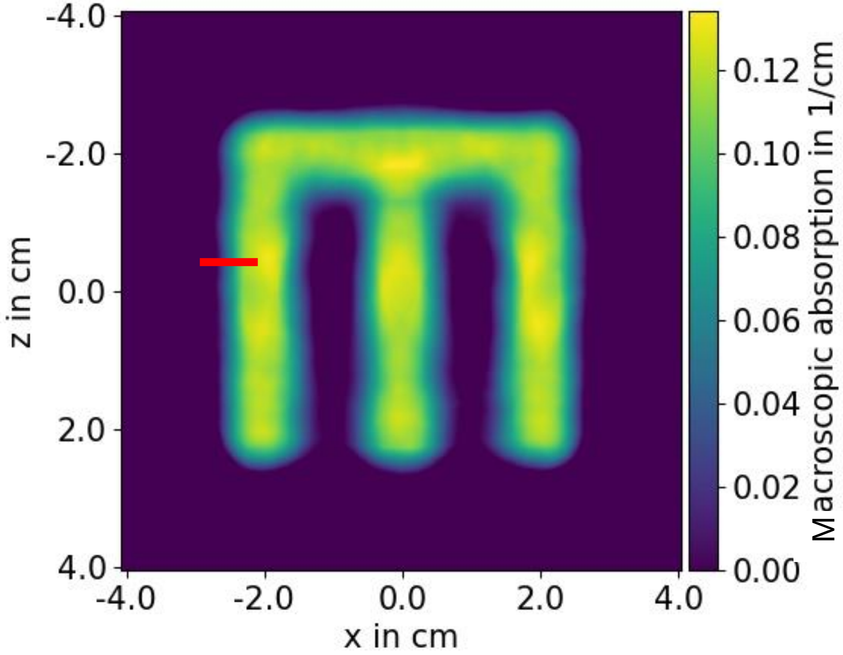
Resolution box:
Spatial resolution

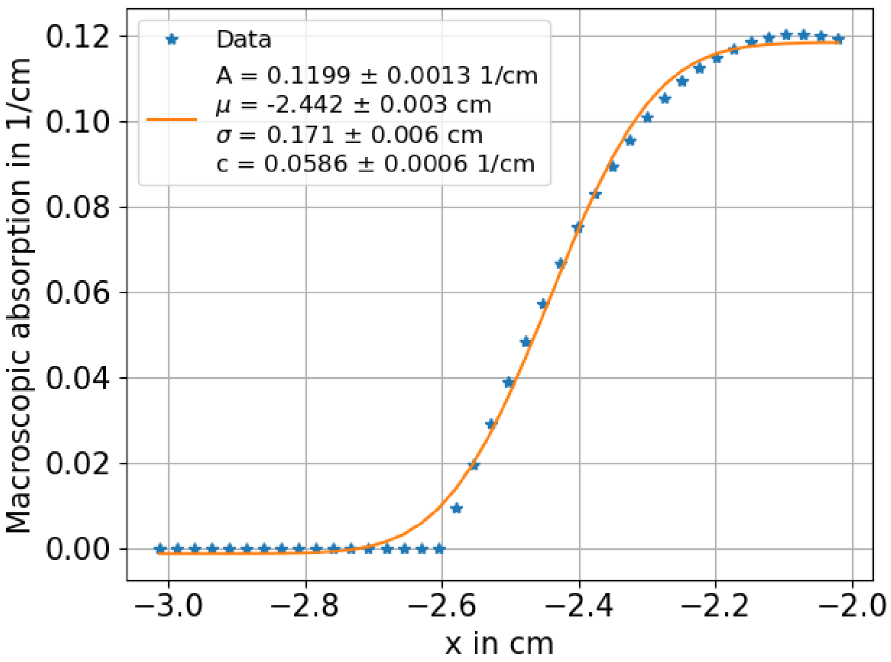




E-like Object

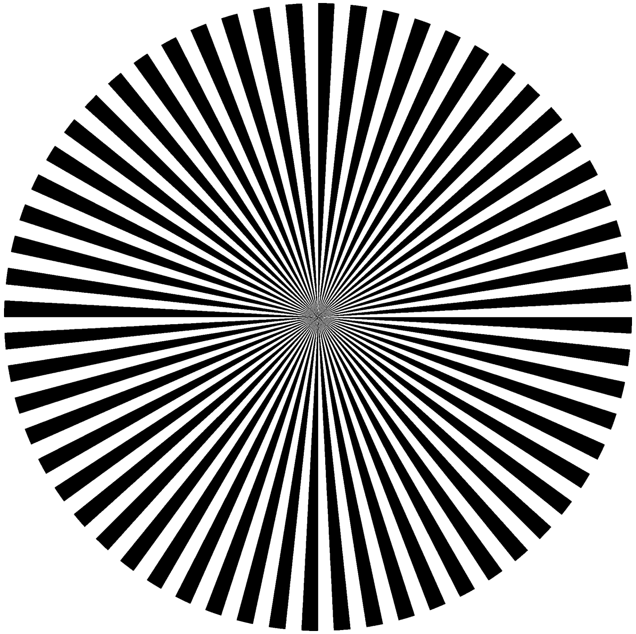
- Fit single error function $f(x) = \frac{A}{2} \cdot erf\left(\frac{x-\mu}{\sigma}\right) + c$ to edge of E
- Use parameter specifying edge width σ
- Resulting $\sigma = (1.91 \pm 0.04)\mathrm{mm}$

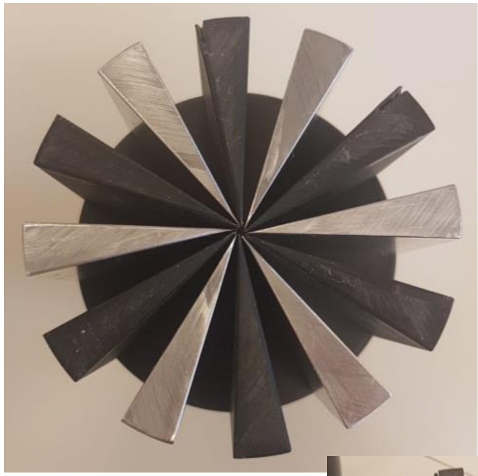


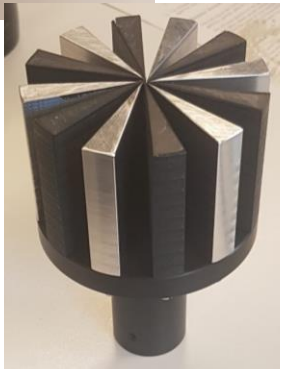


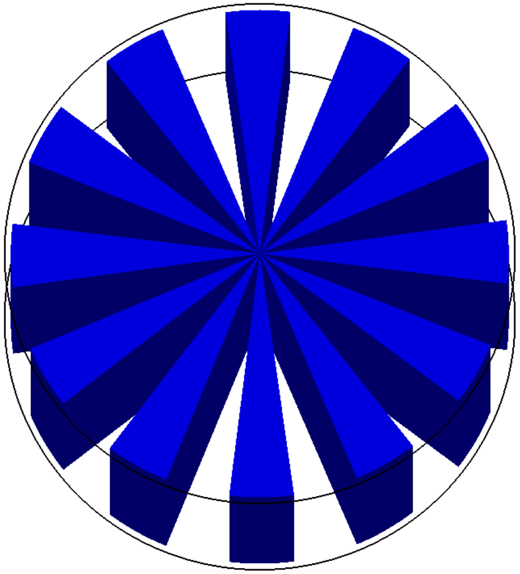
Siemens Star

- Determine radius at which segments are no longer distinguishable



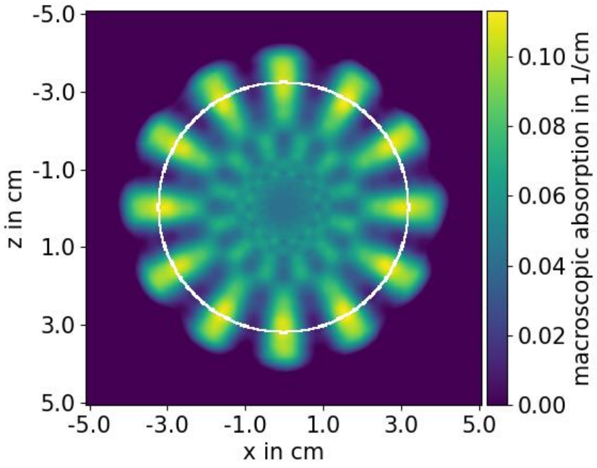


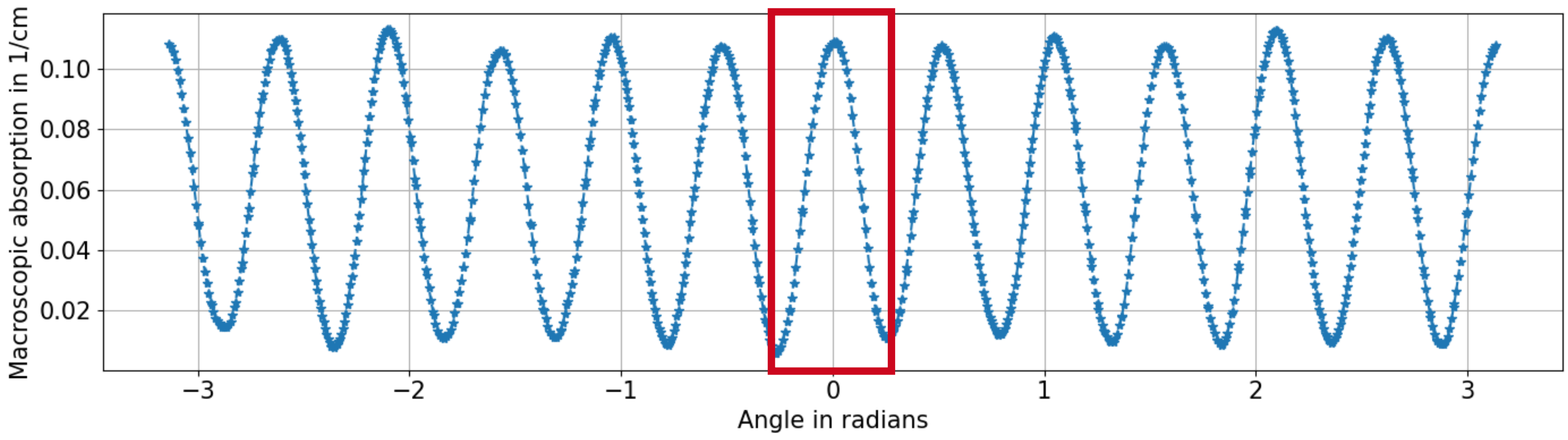




Extracting Values for the Analysis

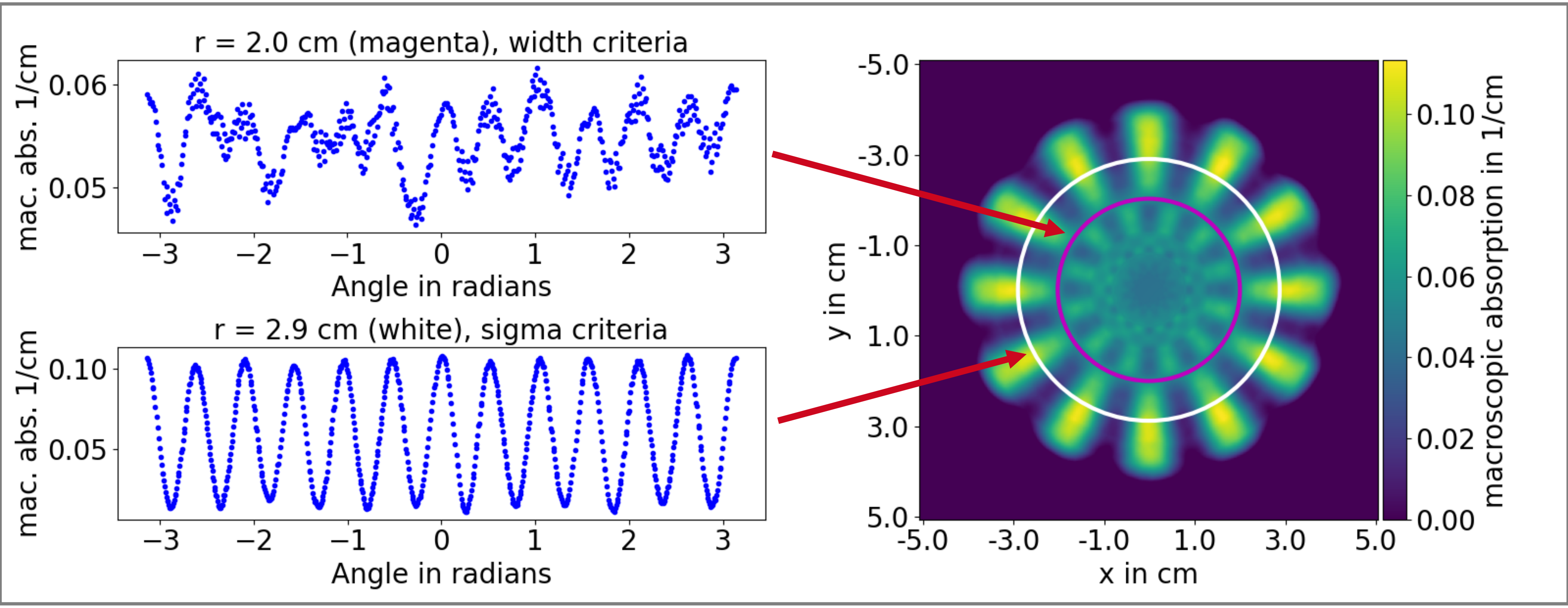
- Extract absorption values along a circle with radius r from tomography image
- Calculate spatial resolution from radius by $\frac{r \cdot \pi}{n_{Segments}}$
- Fit one peak/segment with or w.o. offset





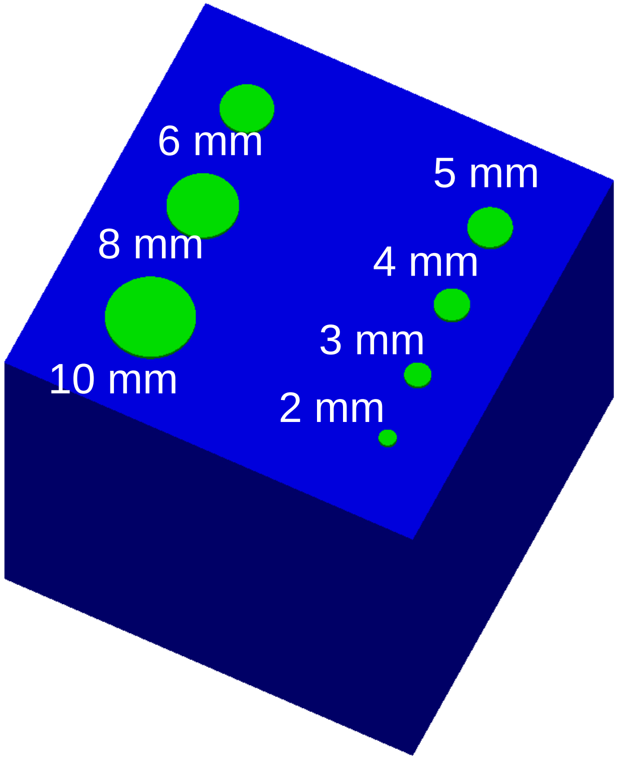
Comparison Values Cut Radius Sigma Criteria

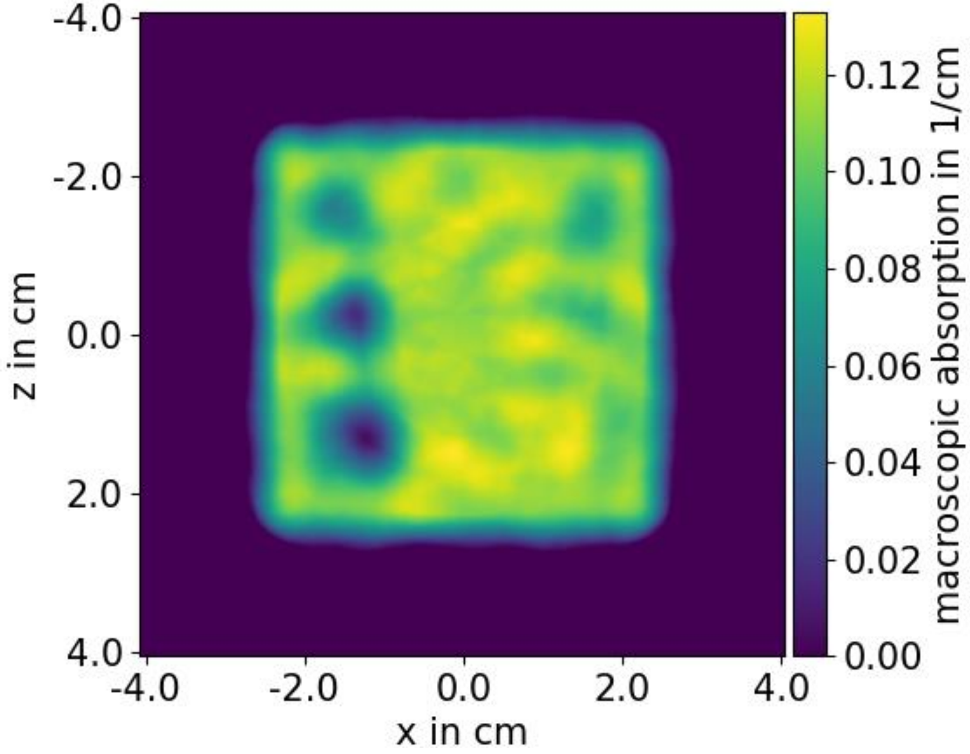
- Width criterion looks closer into the Siemens star – absorption values not smooth
- Sigma criterion limited by absorption values moving closer together



Resolution Box

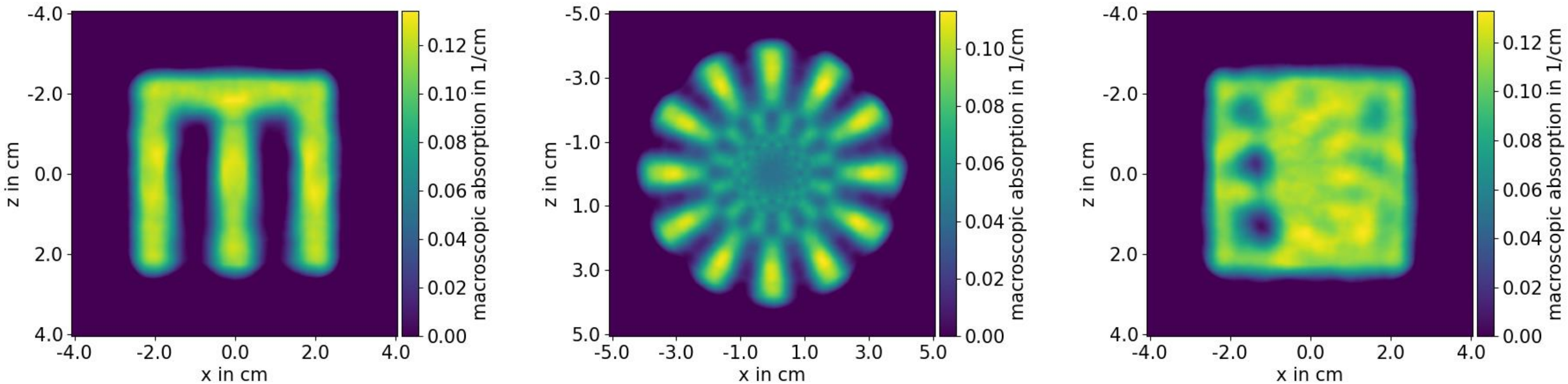
- Cube 5x5x5 cm with differently sized holes
- 5-6 mm diameter holes visible
- 8 mm diameter hole with absorption dropping to ~0 1/cm





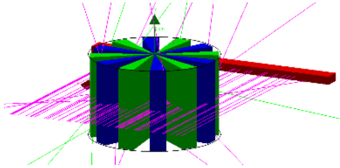
Overview Results

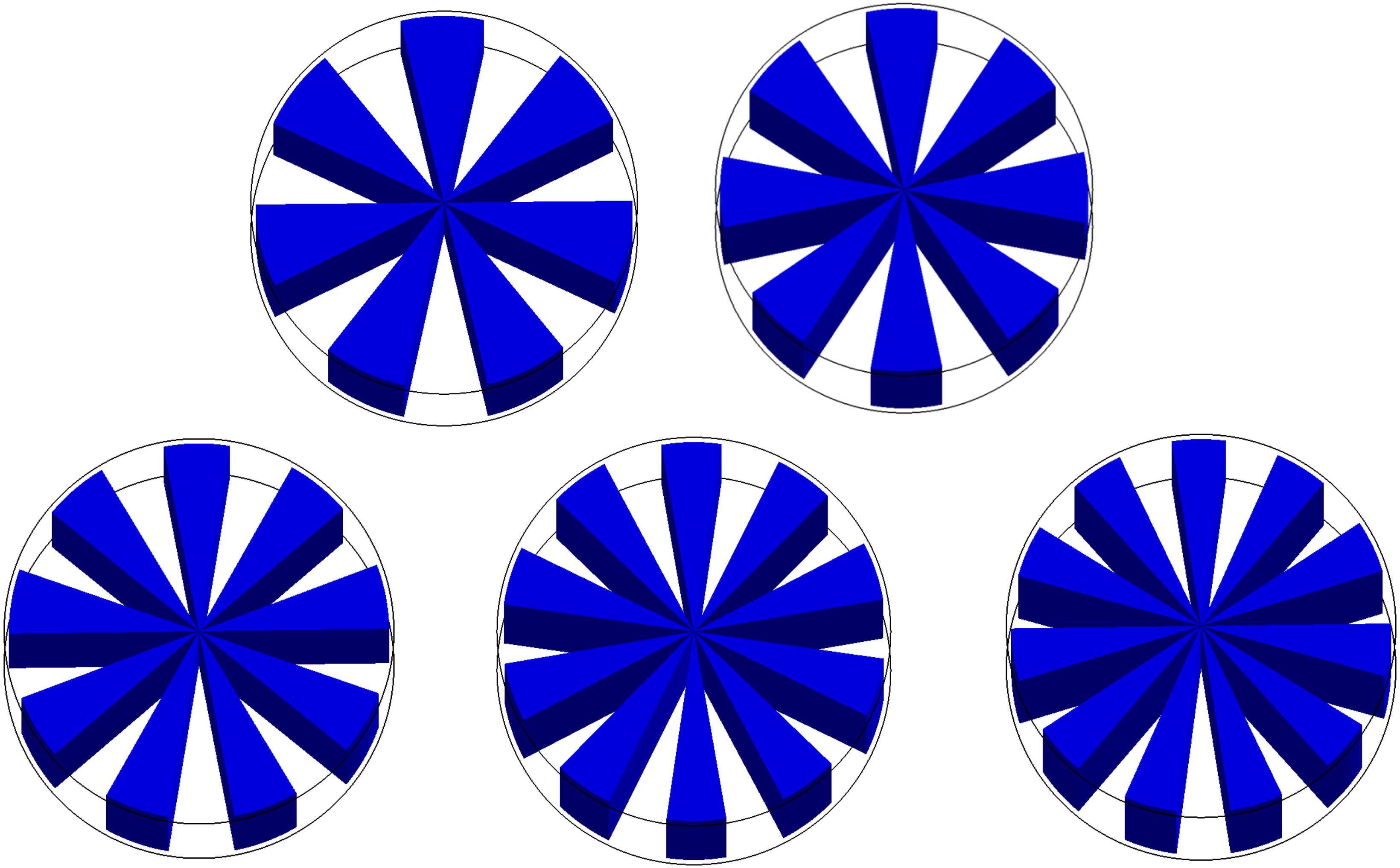
Test object	Spatial resolution	Cut radius	Edge width
Resolution box	5-6 mm	-	-
Siemens star - sigma criteria	7.6 mm	2.9 cm	(4.80 ± 0.10) mm
Siemens star - width criteria	(5.3 ± 0.5) mm	(2.01 ± 0.17) cm	(1.9 ± 0.6) mm
E	-	-	(1.91 ± 0.04) mm



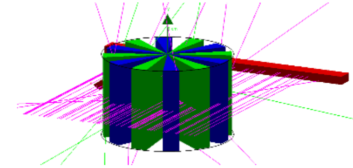
- Enables the evaluation of other detector geometries (e.g. 5x3 pixel)

Siemens Stars – Varying nSegments





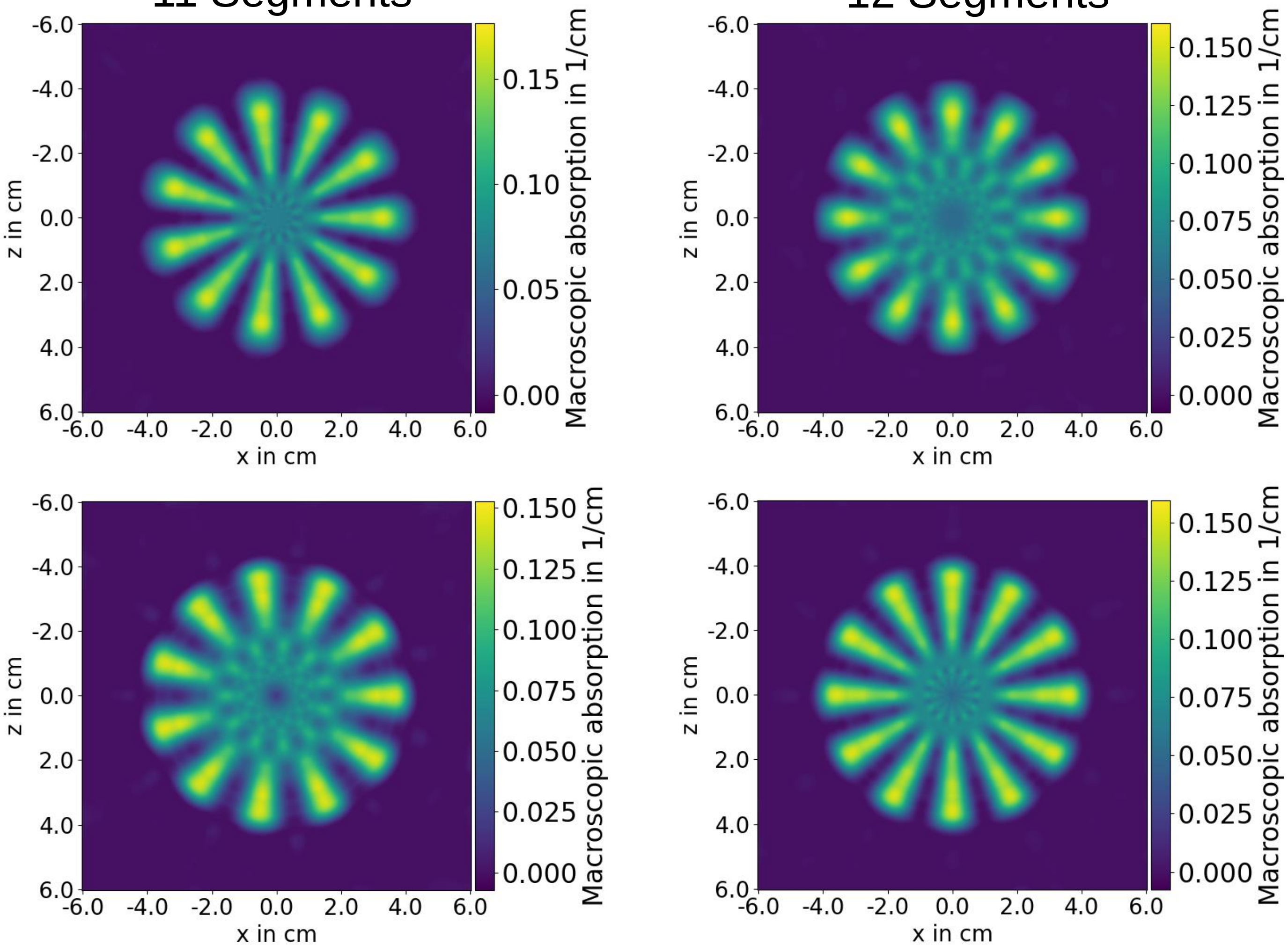
Comparison different nSegments



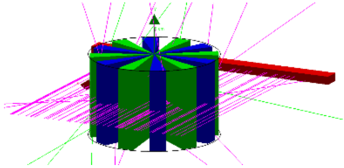
11 Segments | 12 Segments

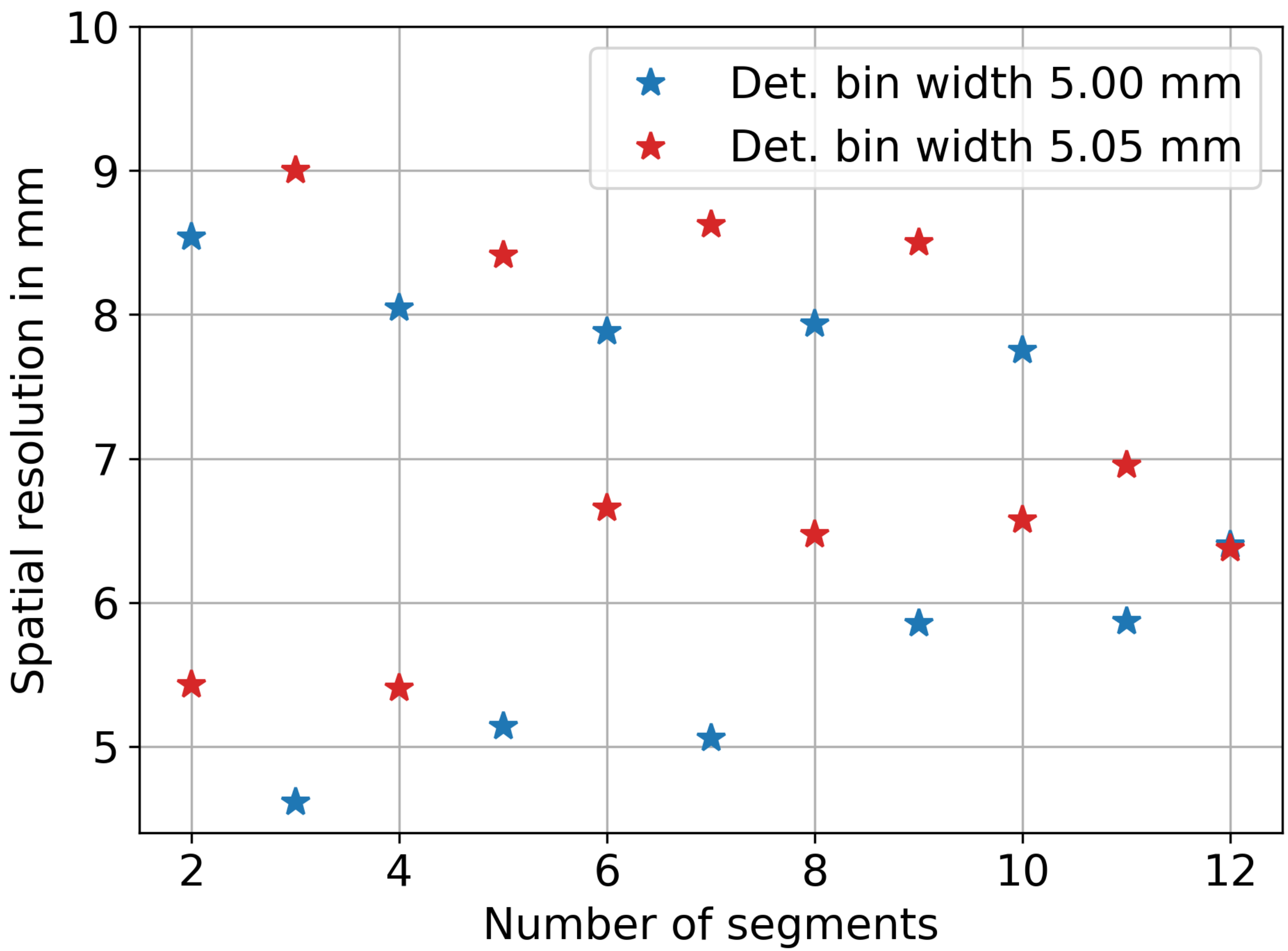
Detector bin width 5.00 mm

Detector bin width 5.05 mm

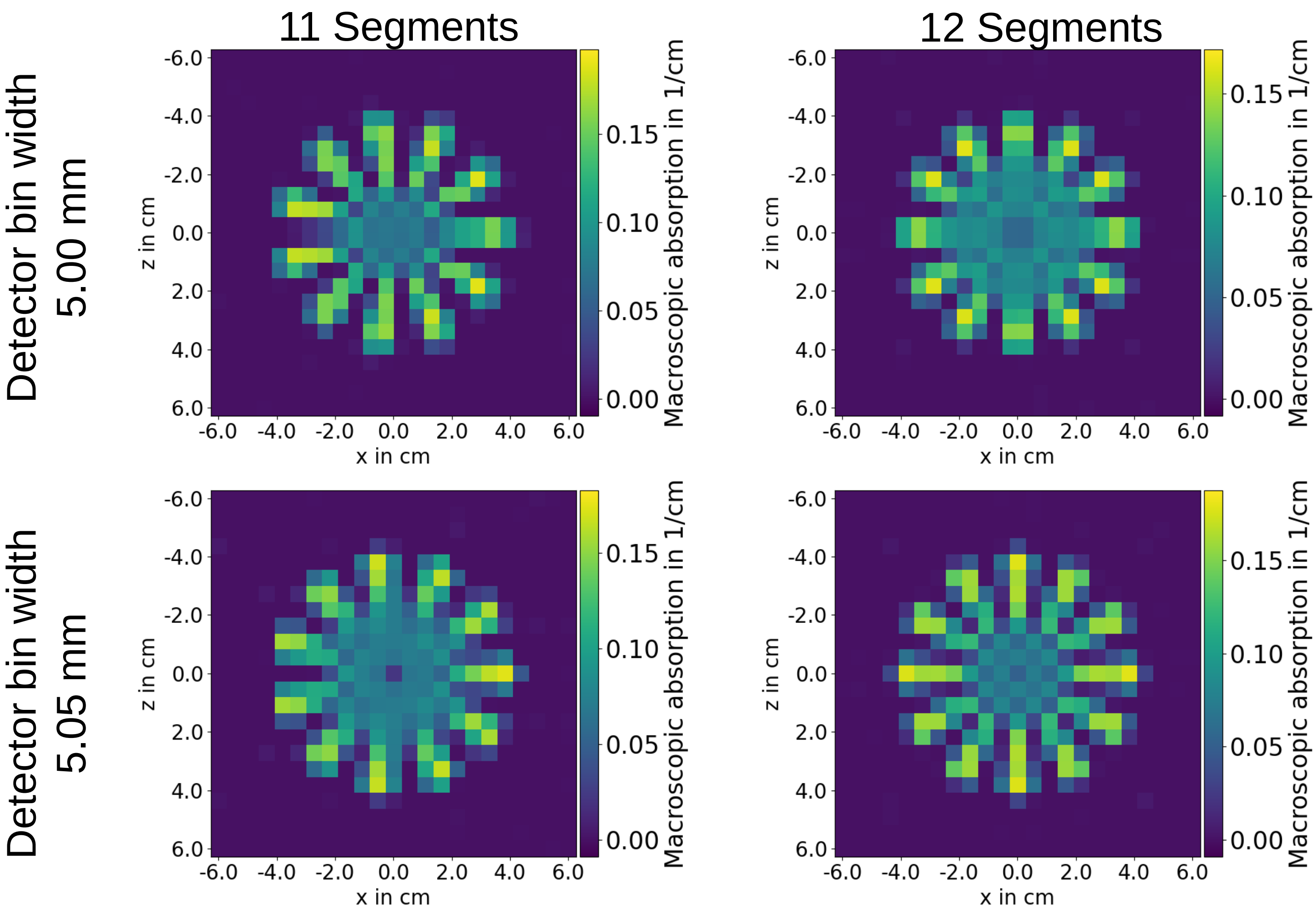


Spatial Resolution - nSegments

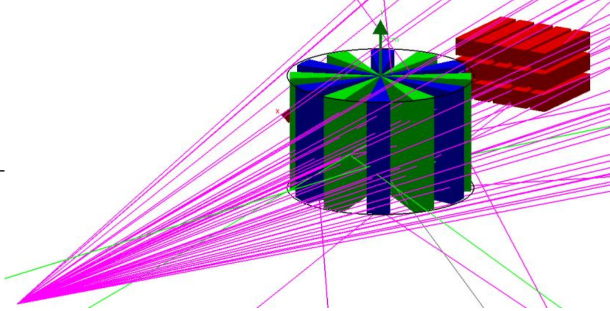




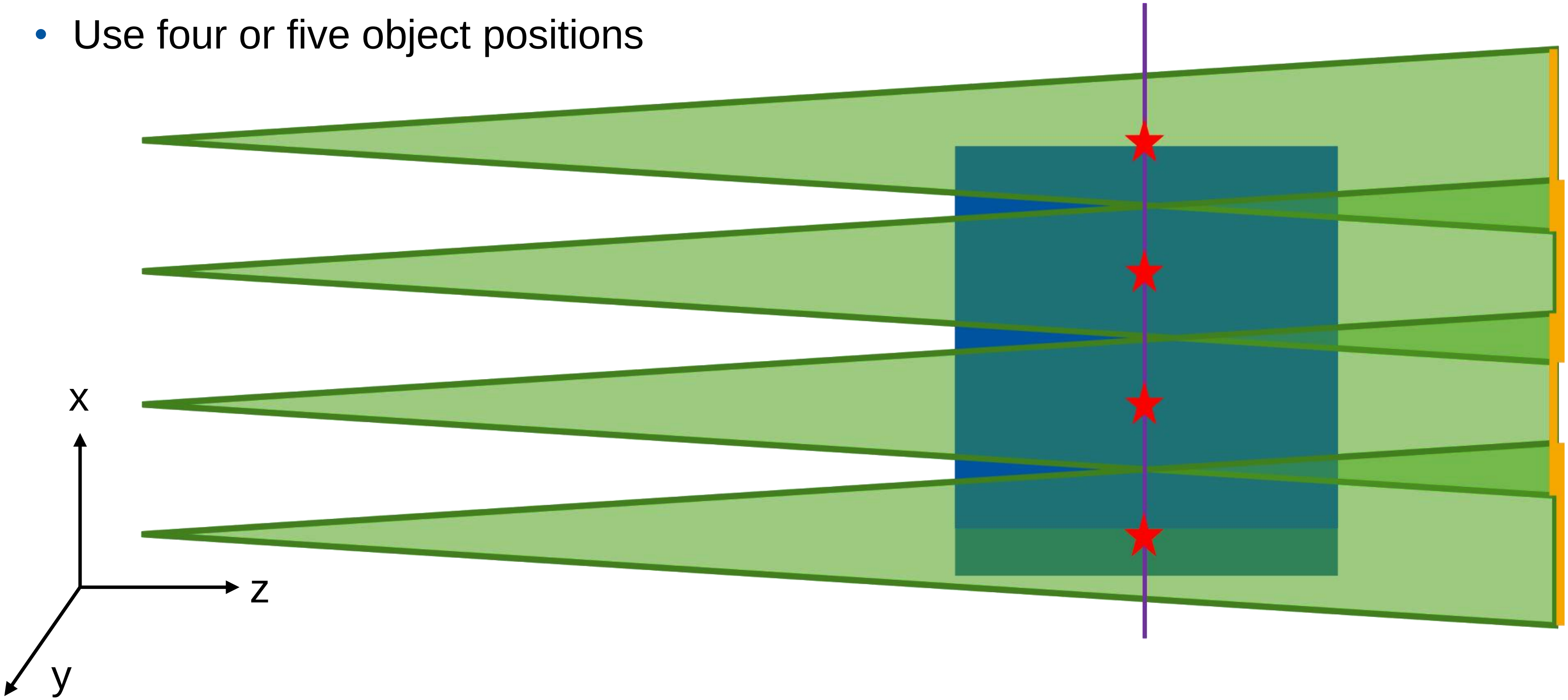
Matching Detector Pixel Positions to Segments



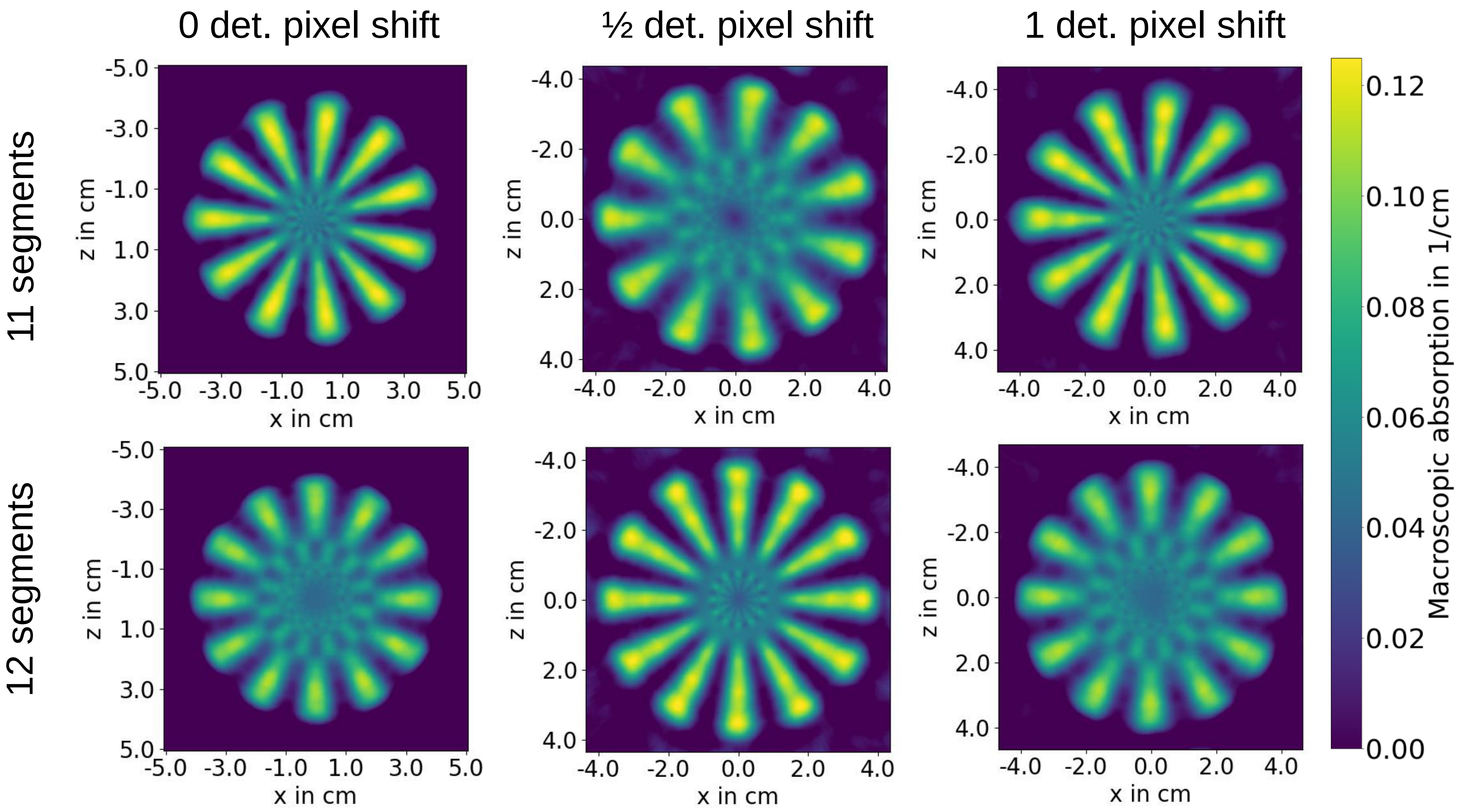
Siemens Stars – Realistic Detector



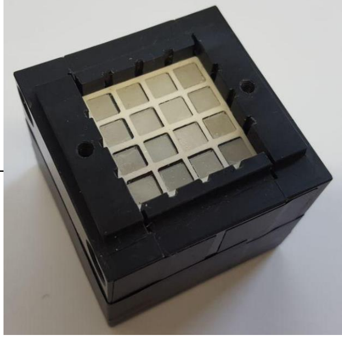
- Evaluate influence of object positions for images of Siemens stars
- Use four or five object positions



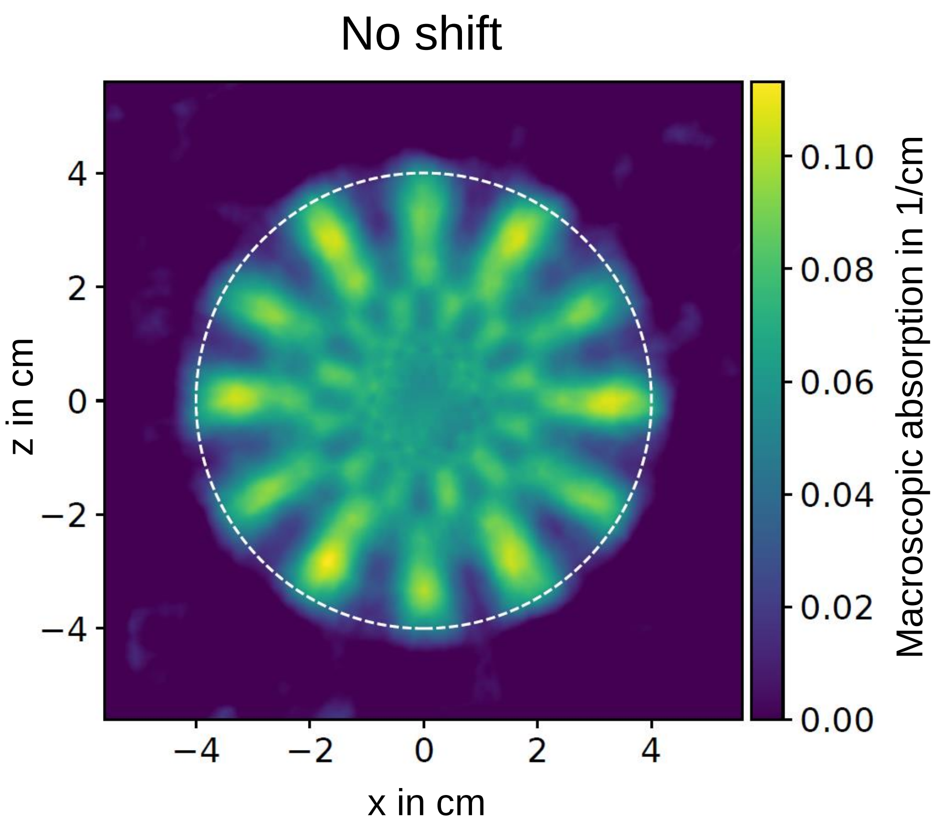
Siemens Stars with Shifted Object Positions

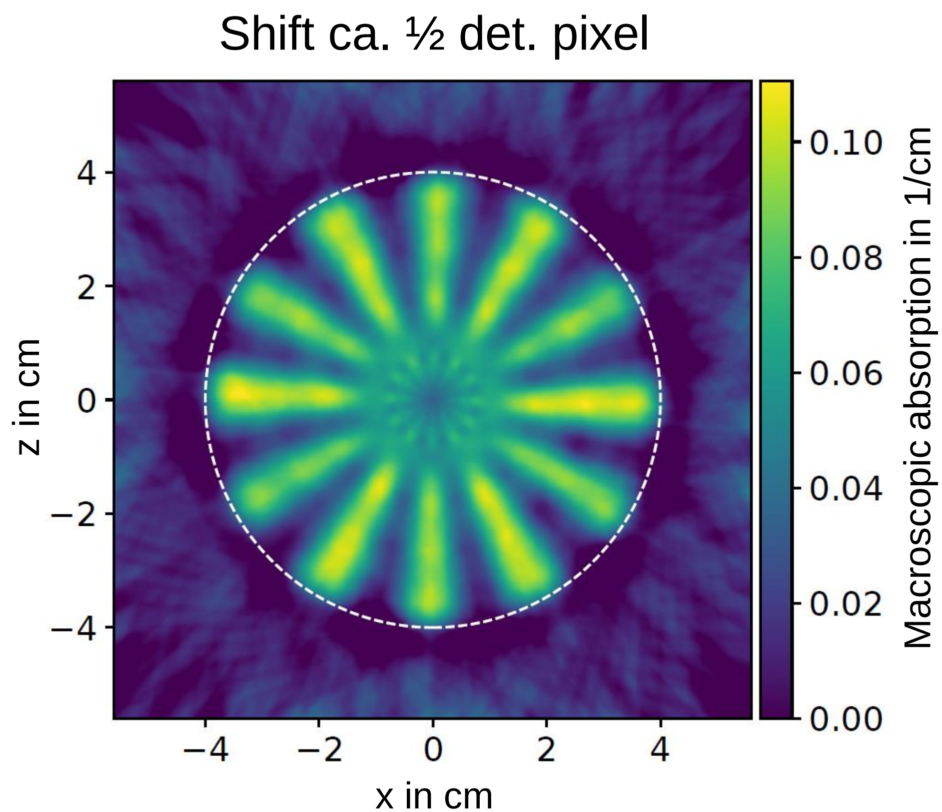


Measurements Siemens Star



- Material of segments alternate between aluminium and PVC
- Four measured object position with interpolation for no shift

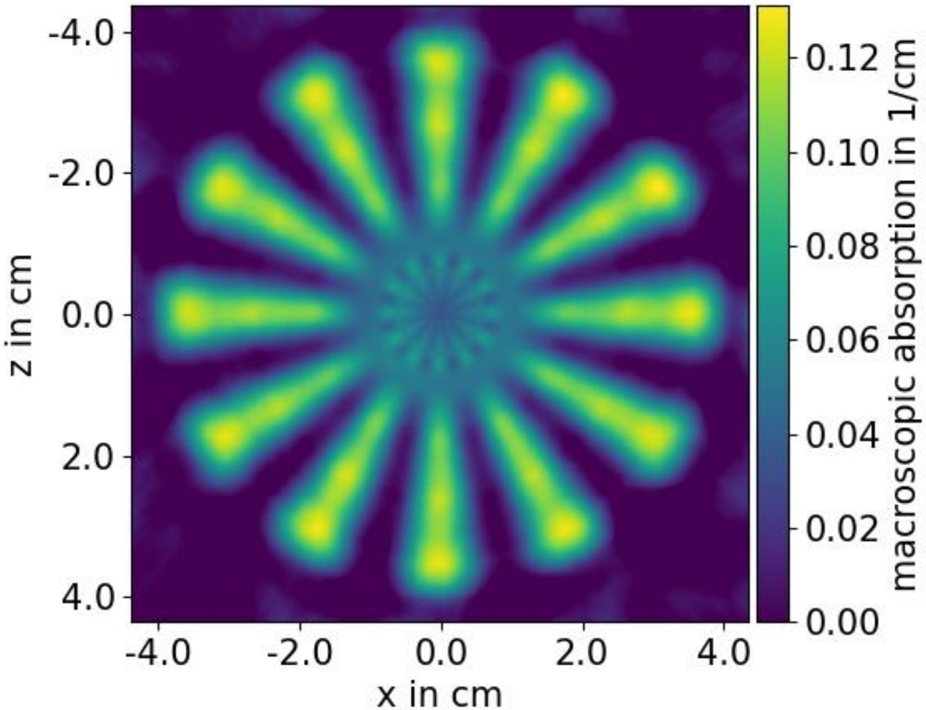




Measurements by Nina Höflich

Summary and Outlook

- Created tomographic images with neutrons and gammas simultaneously
- Particles and detector responses simulated with GEANT4, tomographic reconstruction done with ASTRA Toolbox
- Developed quality criteria for three different objects
- Object positions can heavily influence image quality
- Possibility to investigate new detector arrangements for larger detector (8x8 or 5x3)
- Try slightly distorted setups



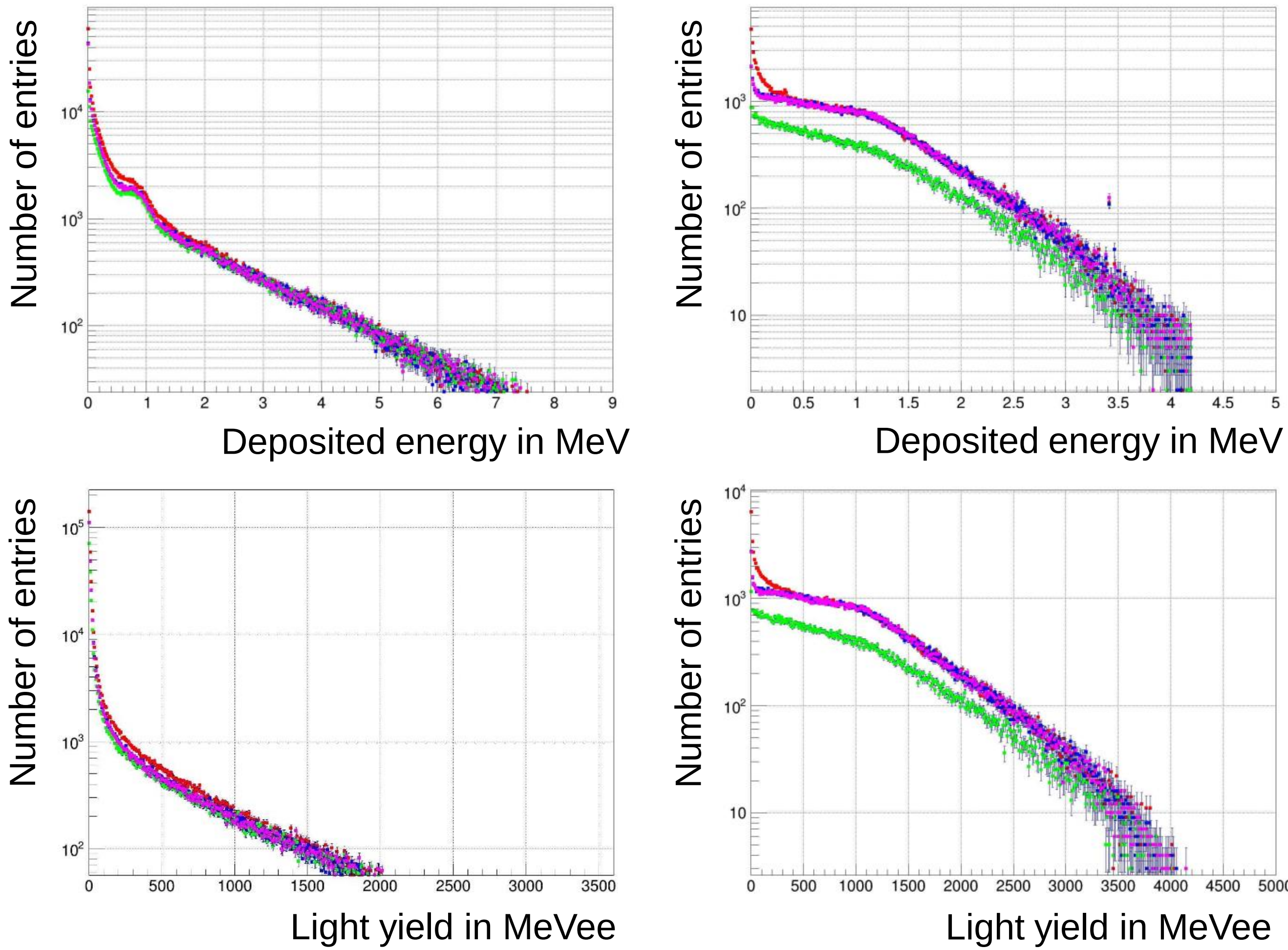
Appendix

Comparison Detector Variations

- Red: Full simulation
- Blue: Only detector box
- Magenta: Simple PVC box
- Green: Only scintillator crystals

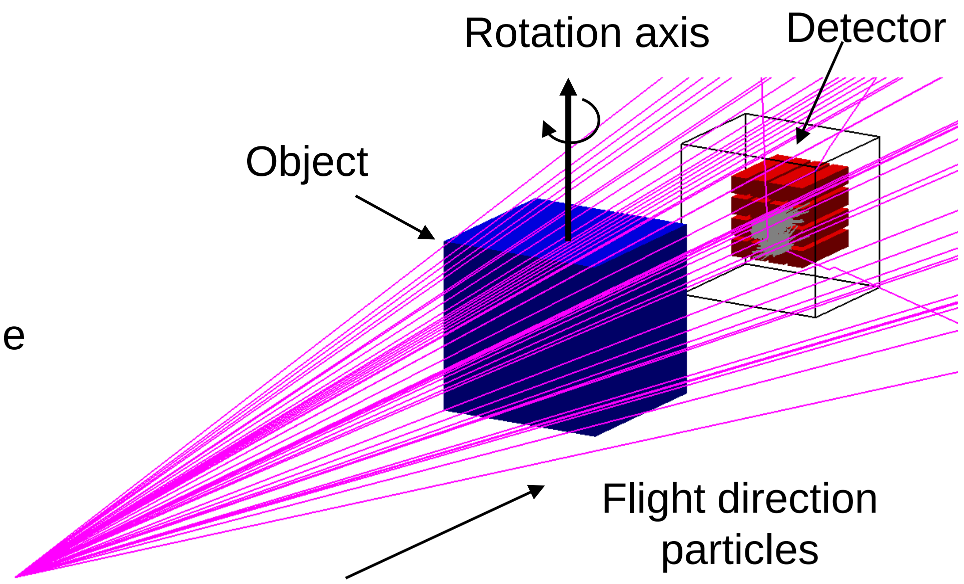
ISO8529 neutrons

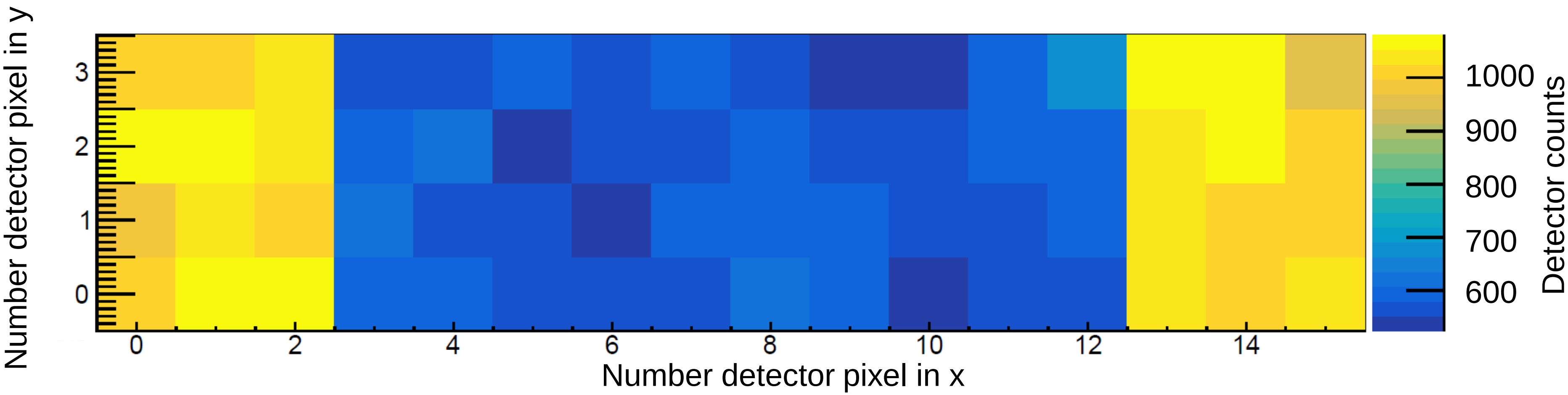
4.44 MeV gammas



Generating Particle Counts with GEANT4

- Simulation of particles, objects and detectors with GEANT4
- Detector response:
  - Idealized: Store exact position of particle
  - Realistic: Store deposited energy and scintillation light





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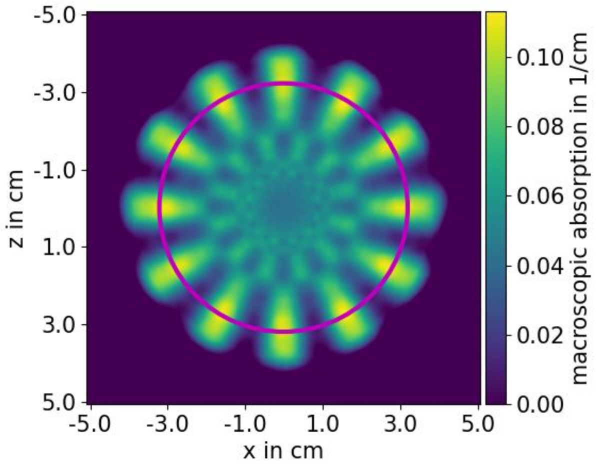
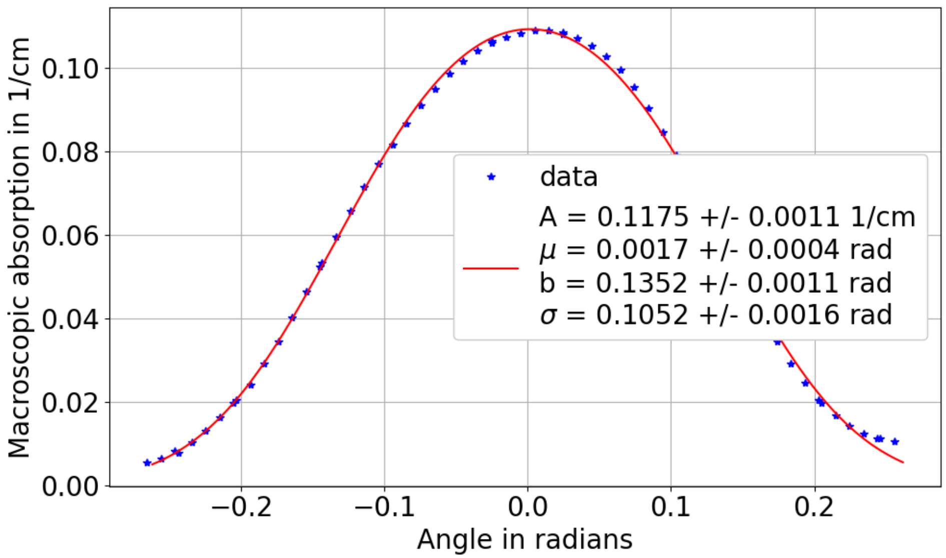
Siemens Star – Sigma Criterion

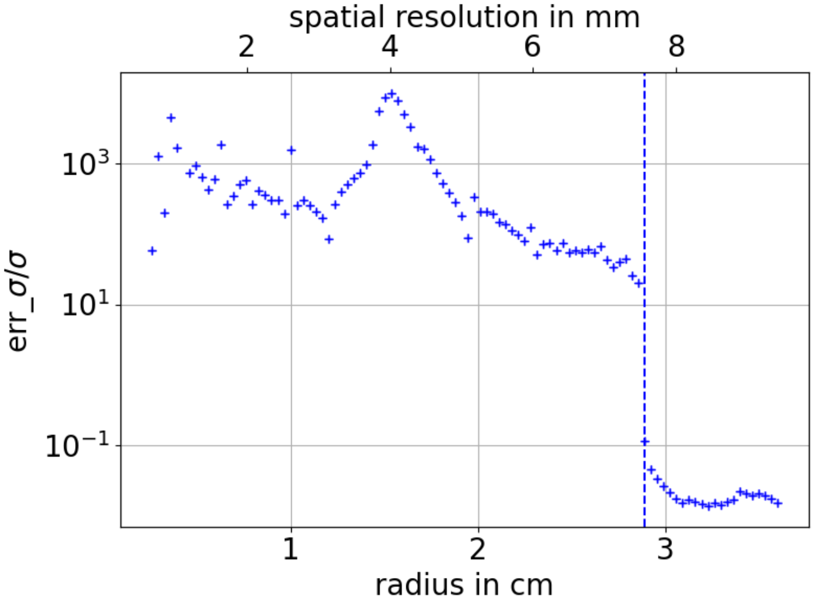
- Fit two sided error function without offset to segment

$$f(x) = \frac{A}{2}\left(erf\left(\frac{x-\mu+b}{\sigma}\right) - erf\left(\frac{x-\mu-b}{\sigma}\right)\right)$$

- Determine relative error on sigma parameter
- This image: Cut radius 2.9 cm, spatial resolution 7.6 mm
- Resulting $\sigma = (4.80 \pm 0.10)mm$







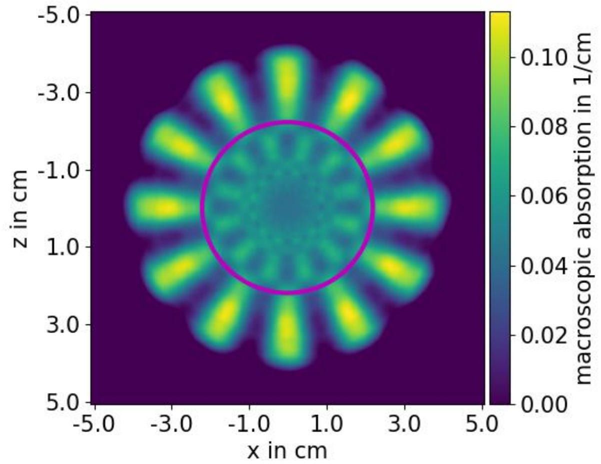
Physics Institute III B

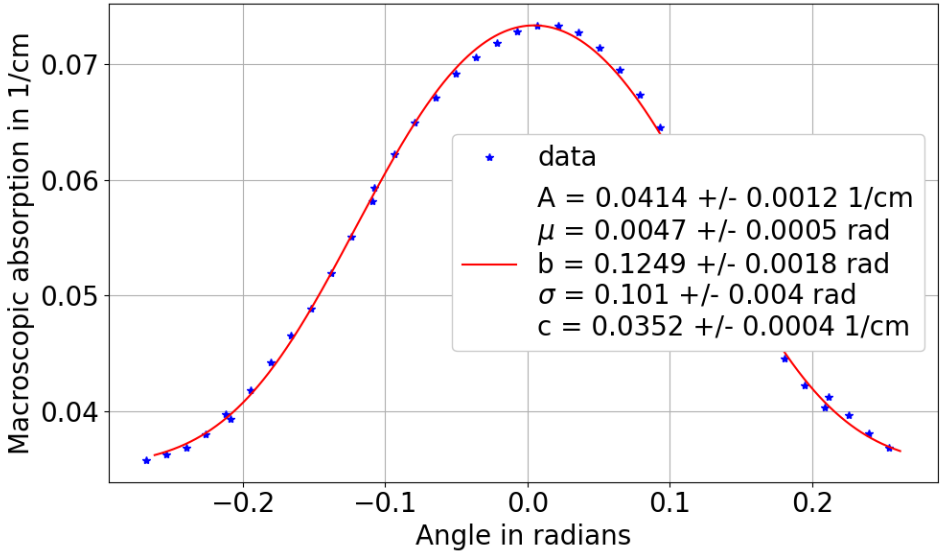
Siemens Star – Width Criterion

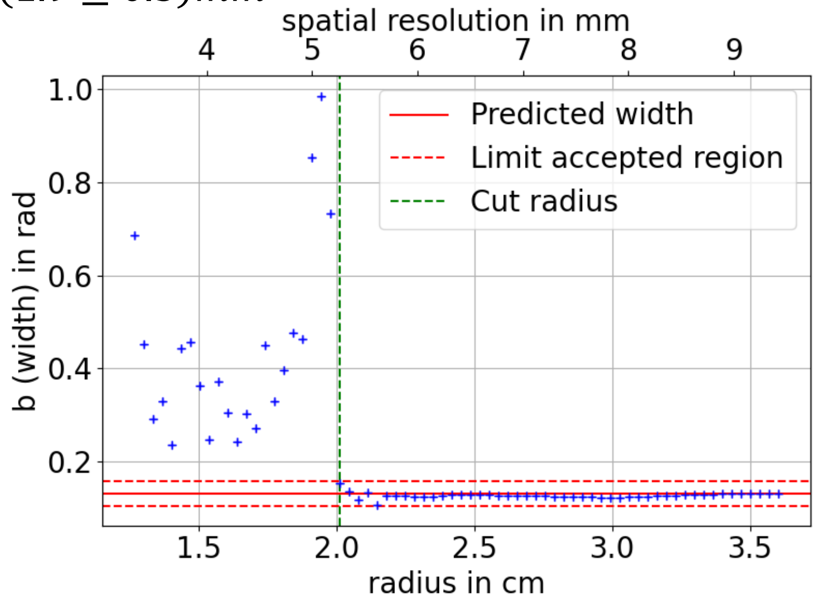
- Fit two-sided error function with offset to segment

$$f(x) = \frac{A}{2}\left(erf\left(\frac{x-\mu+b}{\sigma}\right) - erf\left(\frac{x-\mu-b}{\sigma}\right)\right) + c$$

- Use width of segment b
- This image: Cut radius 2.0 cm, spatial resolution 5.3 mm
- Resulting $\sigma = (1.9 \pm 0.4(stat.) \pm 0.4(sys.))mm = (1.9 \pm 0.5)mm$







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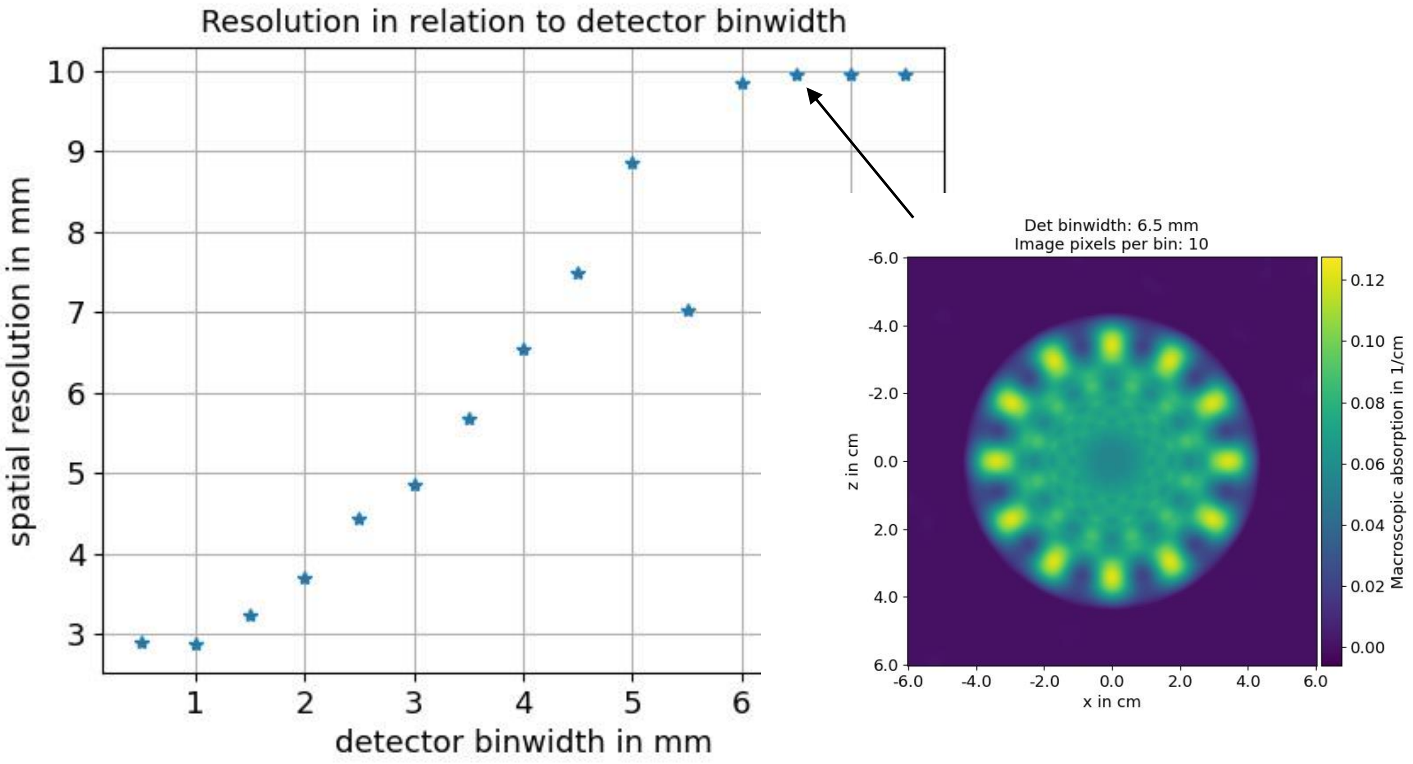
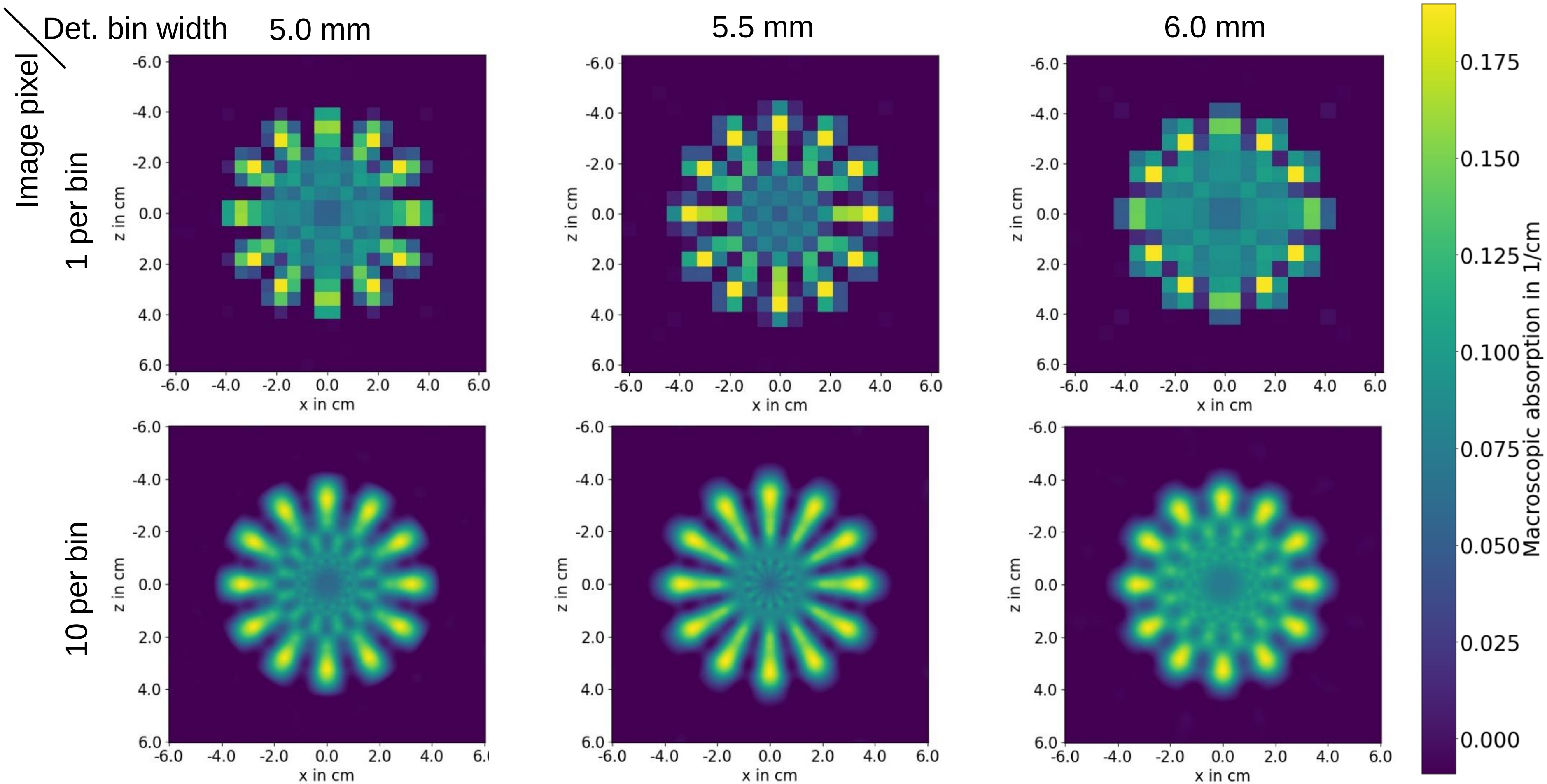
Dependency of the Resolution from the Detector Bin Width

- Find spatial resolution for multiple detector bin widths
- Spatial resolution of 10 mm corresponds to maximum radius of Siemens Star



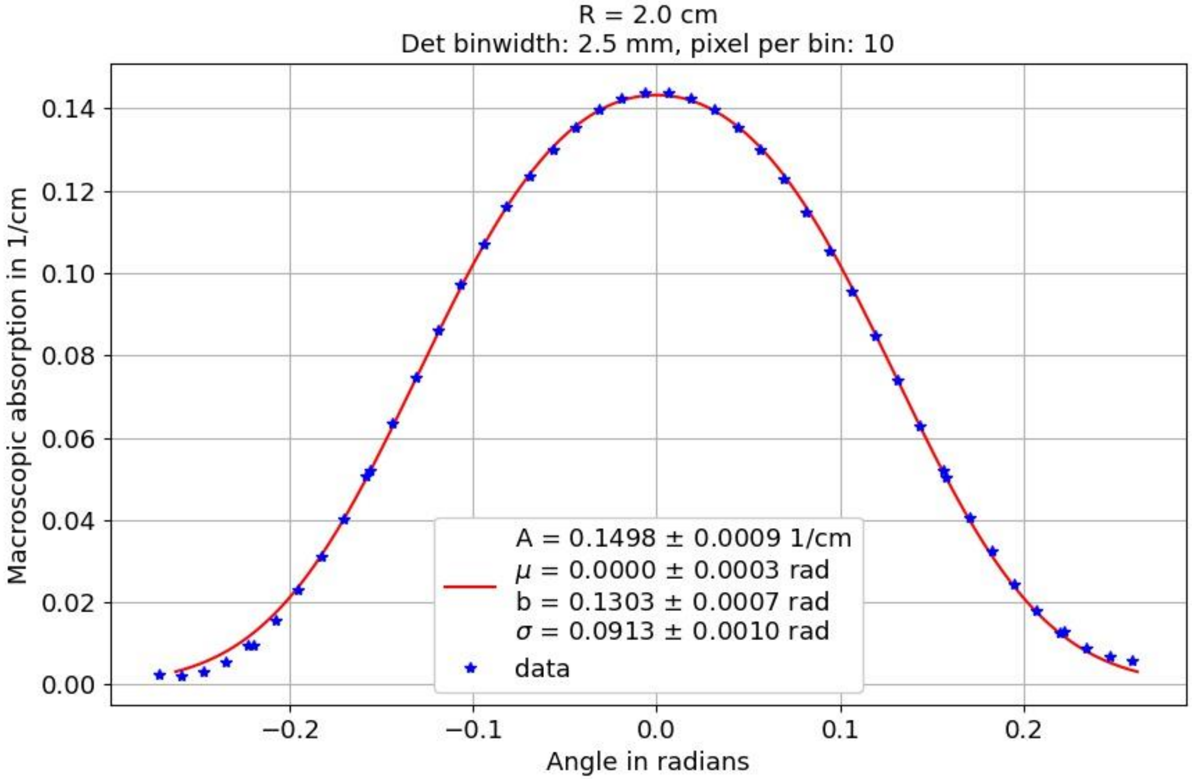
Outliers in Resolution

- If segments of Siemens Star fit well with binning, resolution gets unexpectedly fine

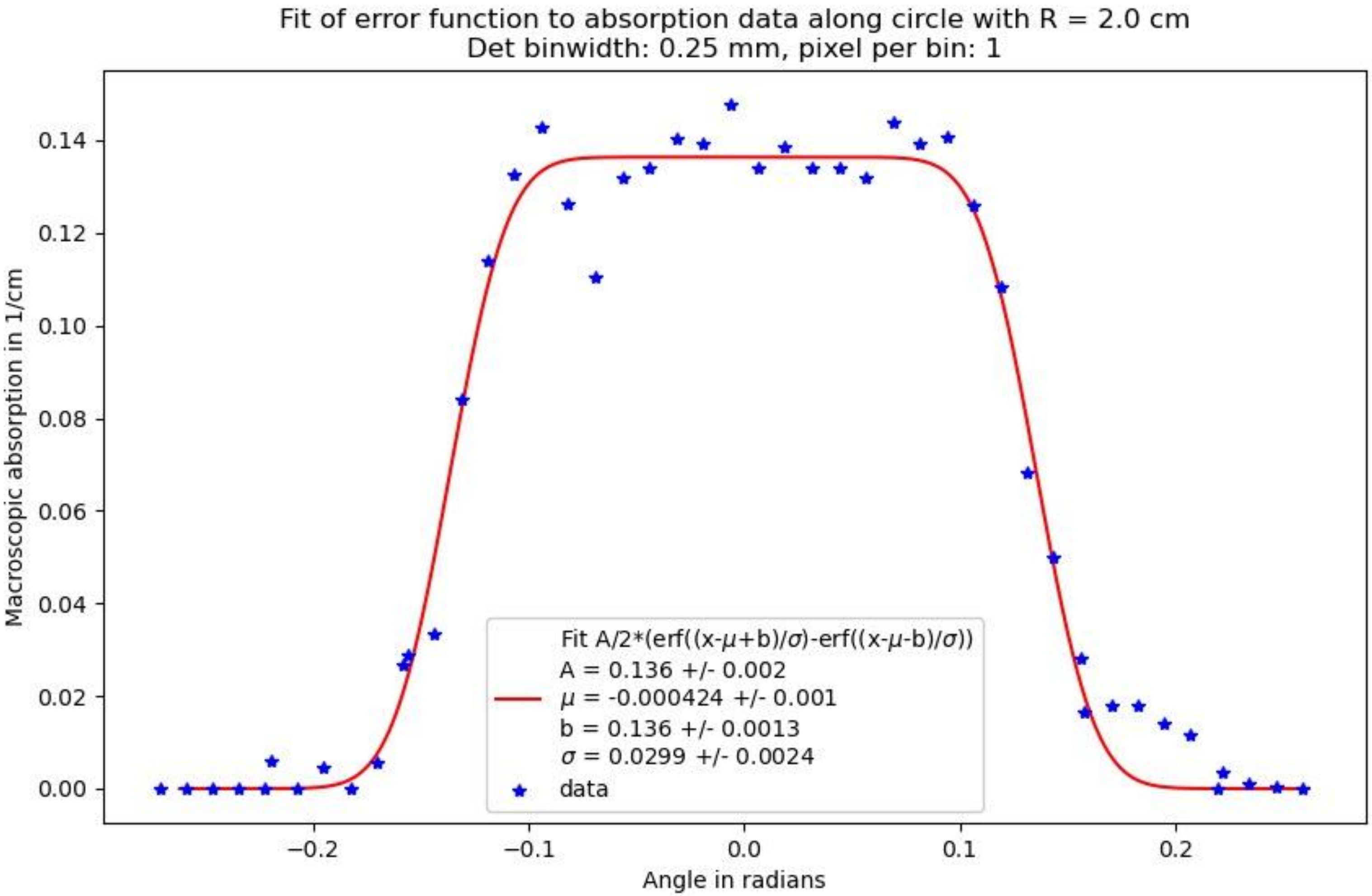


Error Function Fit

- Fit function: $\frac{A}{2}\left(erf\left(\frac{x-\mu+b}{\sigma}\right)-erf\left(\frac{x-\mu-b}{\sigma}\right)\right)$
- Parameters:
  - A: Amplitude
  - μ: Center
  - b: Width
  - σ: Rise-/Fall time

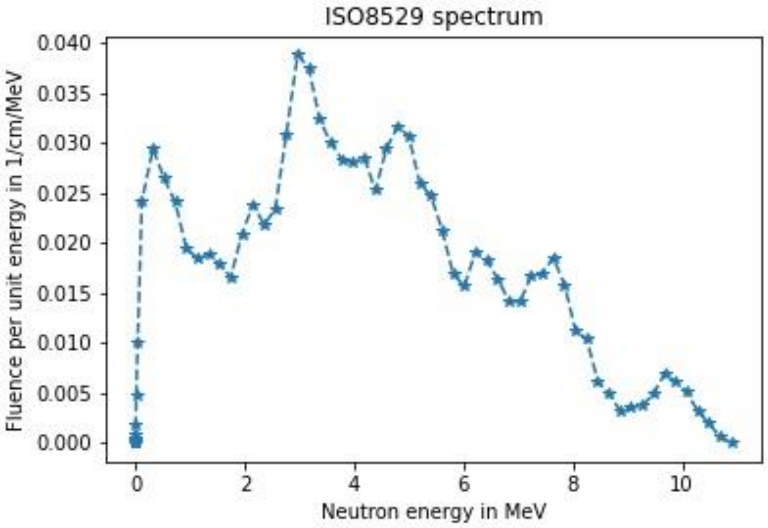


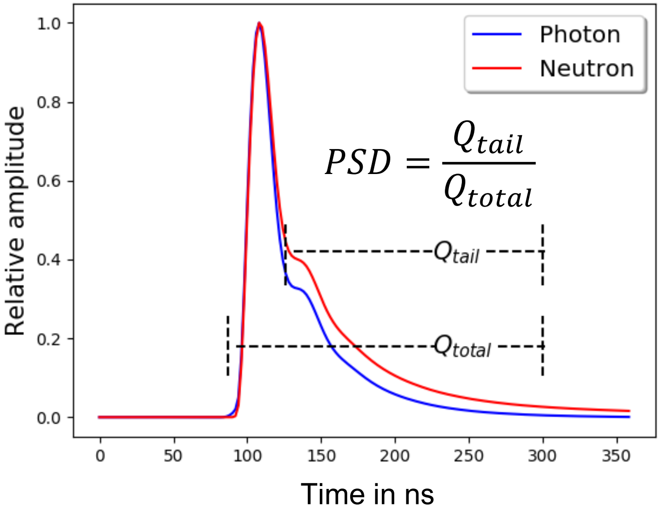
Error Function Fit, Finer Binning



Americium-Beryllium Source

- AmBe source (4.44 MeV gammas, ISO8529 spectrum for neutrons)
- Separation of gammas and neutrons possible with stilbene via Pulse Shape Discrimination (PSD)
- Simultaneous measurements with gammas and neutrons possible



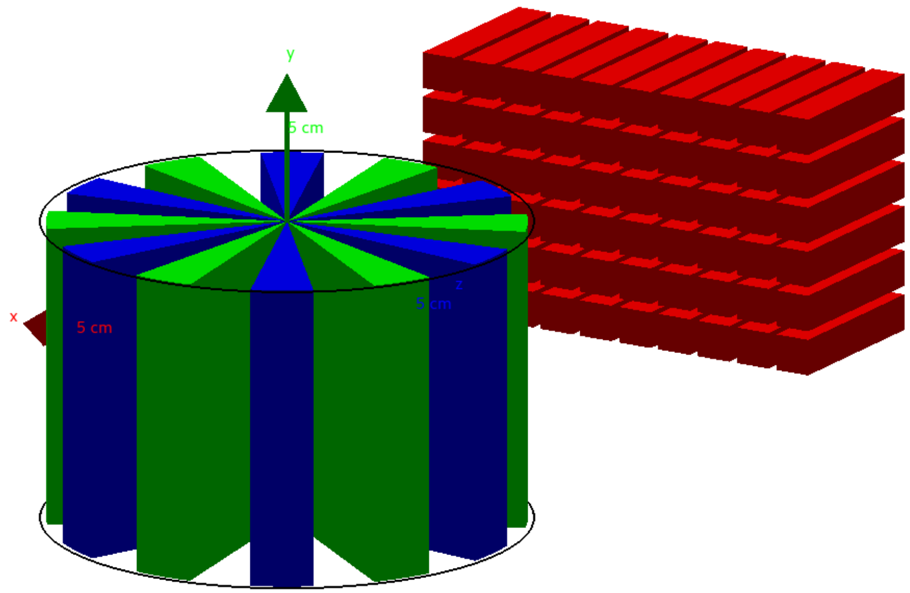


Christian Teichrib

Physics Institute III B

Manipulated Detector

- Goal: Find detector setup which increases detector resolution significantly
- Simulate different detector setups and determining the change in resolution
- Central parameters
  - Number of detector pixel in x and y
  - Number of object positions
  - Overlap of object positions
  - Size of detector pixel
  - Material of detector pixel



Physics GEANT4

- Use high precision neutron package
- HP package settings:
  - Skip missing isotopes: True
  - Do not adjust final state: True
  - Use Only Photo Evaporation: False
  - Neglect Doppler: False
  - Produce fission fragments: False
  - Use Wendt fission model: False
  - Use NRESP71 model: True